Drifting Fish Aggregating Devices of the Atlantic and Indian Oceans : modalities of use, fishing efficiency and potential management

Alexandra Maufroy

Collège Doctoral du Languedoc-Roussillon

THESE

Pour obtenir le grade de

Docteur

Délivré par l'Université de Montpellier

Préparée au sein de l'école doctorale GAIA
Et de l'unité de recherche UMR MARBEC

Spécialité EFSA

Présentée par: Alexandra MAUFROY

Drifting Fish Aggregating Devices of the Atlantic and Indian Oceans: modalities of use, fishing efficiency and potential management

Soutenue le 30 Juin 2016 devant le jury composé de:

Mme Jocelyne FERRARIS, IRD, UMR Entropie, *Rapporteur*
M. Paul MARCHAL, Ifremer Centre Manche Mer du Nord, *Rapporteur*
M. Didier GASCUEL, Agrocampus Ouest Rennes, *Examinateur*
M. Roger PRADEL, CEFE - CNRS, *Examinateur*
M. Nicolas BEZ, IRD - UMR MARBEC, *Directeur de thèse*
M. Emmanuel Chassot, IRD - UMR MARBEC, *Co-Directeur de thèse*
M. David M. KAPLAN, VIMS (USA), *Invité*

IRD Institut de recherche pour le développement

marbec marine biodiversity exploitation & conservation

FRANCE FILIERE PECHE

A Tom.
Sans qui cette thèse n’existerait pas.
Mais sans qui plus rien n’a de sens.

Abstract

Since the mid 1990s, the use of drifting Fish Aggregating Devices (dFADs) by purse seiners, artificial objects specifically designed to aggregate fish, has become an important mean of catching tropical tunas. In recent years, the massive deployments of dFADs, as well as the massive use of tracking devices on dFADs and natural floating objects, such as GPS buoys, have raised serious concerns for tropical tuna stocks, by-catch species and pelagic ecosystem functioning. Despite these concerns, relatively little is known about the modalities of GPS buoy tracked objects use, making it difficult to assess and manage of the impacts of this fishing practice. To fill these knowledge gaps, we have analyzed GPS buoy tracks provided by the three French fishing companies operating in the Atlantic and the Indian Oceans, representing a large proportion of the floating objects monitored by the French fleet. These data were combined with multiple sources of information: logbook data, Vessel Monitoring System (VMS) tracks of French purse seiners, information on support vessels and Local Ecological Knowledge (LEK) of purse seine skippers to describe GPS buoy deployment strategies, estimate the total number of GPS buoy equipped dFADs used in the Atlantic and Indian Oceans, measure the contribution of strategies with FOBs and support vessels to the fishing efficiency of tropical tuna purse seiners, identify potential damages caused by lost dFADs and finally to propose management options for tropical tuna purse seine FOB fisheries. Results indicate clear seasonal patterns of GPS buoy deployment in the two oceans, a rapid expansion in the use of dFADs over the last 7 years with an increase of 4.2 times in the Indian Ocean and 7.0 times in the Atlantic Ocean, possible damages to fragile coastal ecosystems with 10% of GPS buoy tracks ending with a beaching event and an increased efficiency of tropical tuna purse seine fleets from 3.9% to 18.8% in the Atlantic Ocean over 2003-2014 and from 10.7% to 26.3% in the Indian Ocean. Interviews with purse seine skippers underlined the need for a more efficient management of the fishery, including the implementation of catch quotas, a limitation of the capacity of purse seine fleets and a regulation of the use of support vessels. These results represent a first step towards better assessment and management of purse seine FOB fisheries.

keywords: tropical tunas, fishing effort, pelagic ecosystems, Atlantic Ocean, Indian Ocean, Fish Aggregating Devices

Résumé

Depuis le milieu des années 1990, l'utilisation de Dispositifs de Concentration de Poissons (DCP), des objets artificiels spécifiquement mis à l'eau pour agréger des bancs de poissons, est devenue de plus en plus importante pour la pêche au thon tropical à la senne. Cette utilisation massive des DCP, qui s'accompagne d'une utilisation massive de dispositifs de suivi comme les balises GPS et les balises échosondeurs, est aujourd'hui source d'inquiétude pour les stocks de thons, les prises accessoires mais aussi pour le fonctionnement des écosystèmes pélagiques. Cependant, les modalités d'utilisation des DCP et des balises GPS qui servent à les suivre restent mal connues, ce qui complique considérablement l'évaluation et la gestion des impacts de ces pratiques de pêche. Afin d'améliorer les connaissances actuelles de la pêcherie, les positions des balises GPS utilisées par les 3 armements français dans les océans Atlantique et Indien, constituant une part significative des DCP utilisés dans ces deux océans, ont été analysées. Ces données ont été combinées avec des multiples sources d'information : les livres de bord, les trajectoires VMS des senneurs français ainsi que des entretiens avec les patrons français. Elles nous permettent de mieux comprendre les stratégies de mise à l'eau des DCP et des balises, d'estimer le nombre d'objets flottants utilisés par les flottes de senneurs dans les océans Atlantique et Indien, de mesurer la contribution des DCP et des navires auxiliaires à l'efficacité de pêche des senneurs, d'identifier des destructions potentielles d'habitats par les DCP échoués et pour finir de proposer des solutions de gestion pour la pêcherie. Les résultats montrent une importante saisonnalité dans les mises à l'eau des deux océans, une croissance rapide du nombre de balises GPS au cours des 7 dernières années puisqu'elle est multipliée par 4.2 dans l'Océan Indien et 7 dans l'Océan Atlantique, des dommages possibles causés à des écosystèmes côtiers fragiles avec une probabilité d'échouage de l'ordre de 10% et finalement une augmentation de l'efficacité de pêche entre 2003 et 2014 de l'ordre de 3.8-18.8% dans l'Océan Atlantique et 10.7%-26.3% dans l'Océan Indien. Les entretiens avec les capitaines des senneurs soulignent la nécessité d'une gestion plus efficace de la pêcherie, avec entre autres l'instauration de quotas, une régulation de la capacité de la flotte de senneurs et un meilleur suivi des navires auxiliaires. Les résultats obtenus constituent les premières étapes nécessaires à une meilleure gestion de la pêche sous objet flottant.

mots clés: thons tropicaux, effort de pêche, écosystèmes pélagiques, Océan Atlantique, Océan Indien, Dispositifs de Concentration de Poissons

Remerciements

Cette étude a été financée par France Filière Pêche (http://www.francefilierepeche.fr/) et a bénéficié d'une aide du projet AMPED (Aires Marines Protégées pour Espèces qui se Déplacent beaucoup, www.amped.ird.fr), financé par l'Agence Nationale de la Recherche (ANR) dans le cadre du programme SYSTERRA ainsi que d'une aide de l'Observatoire Thonier. Une partie des questions abordées dans cette thèse s'inscrit dans le projet CEcoFAD (Catch, Effort, and eCOsystem impacts of FAD-fishing).

Je tiens tout d'abord à remercier mes directeurs de thèse Emmanuel Chassot, David Kaplan et Nicolas Bez. A chacun de vous, merci de m'avoir donné la chance de découvrir cette pêcherie fascinante. Entre découvertes et rebondissements, la route n'a pas été facile mais vous avez su tour à tour me guider, m'accompagner, bousculer mes certitudes parfois, tout en me laissant la liberté d'explorer des pistes qui me tenaient à cœur. J'ai beaucoup appris de ces quatre années passées avec vous.

Je souhaite aussi remercier les membres de l'Observatoire Thonier, pas seulement pour les données sans lesquelles cette thèse n'existerait pas mais aussi pour leur aide et pour leur soutien. En particulier, je remercie Laurent Floch pour son aide précieuse tout au long de ce travail, le temps passé à résoudre les difficultés techniques et à préparer les données. Je remercie également Daniel Gaertner pour sa bienveillance et son aide précieuse pour démêler les inextricables problèmes d'effort de pêche, ainsi qu'Alain Fonteneau et Francis Marsac pour leurs bons conseils et leur relecture de mon dernier chapitre en un temps record.

Je remercie Orthongel (Organisation des producteurs de thon congelé et surgelé, http://orthongel.fr) qui a mis à la disposition de l'IRD les données de position des balises GPS utilisées par les thoniers senneurs français pour suivre leurs objets flottants. Je remercie les instituts Espagnols AZTI (http://www.azti.es/) et IEO (http://www.ieo.es) qui ont mis à notre disposition les données observateurs collectées à bord des senneurs Espagnols ainsi que les données des livres de bord. Je remercie la SFA aux Seychelles pour m'avoir accueillie à deux reprises et pour les informations recueillies sur les navires auxiliaires.

Je remercie chacun des patrons Français ou Espagnols qui m'ont accordé leur temps et leur confiance, pour certains d'entre eux à deux reprises. Vous m'avez aidé à transformer des chiffres en histoires et à donner un autre sens à mon travail, j'espère que les résultats sont à la hauteur de ce que vous m'avez apporté. Je souhaite également remercier toutes les autres personnes avec lesquelles j'ai pu échanger au cours de ce travail (armements, ONG, pêcheurs locaux aux Seychelles, gestionnaires, conserverie) et qui m'ont aidé à y voir plus clair.

Je remercie chacune des personnes rencontrées à l'IRD et à l'Ifremer de Sète, pour tous les bons moments passés ensemble et leur soutien. Merci aux doctorants, aux collègues, au LER dont j'ai croisé la route depuis mon arrivée à Sète.

Enfin, je tiens à remercier mes proches pour leur soutien sans faille. Merci à mes grands parents pour avoir toujours été là et pour m'avoir prêté une oreille attentive. Merci à Sarah-Lise pour les discussions qui m'ont souvent aidé à avancer. Et merci à toi Tom d'avoir traversé ces trois dernières années avec moi, pour la force que tu m'as donnée. Toi que nous avons perdu brutalement et qui nous manquera toujours.

Table of contents

List of figures

General Introduction

Chapter 1

Chapter 2

Chapter 3

Chapter 4

General discussion

List of tables

General Introduction

Chapter 1

Chapter 2

Chapter 3

Chapter 4

General discussion

Synthèse des travaux en français

A- Introduction générale

Les Hommes ont depuis longtemps exploité les ressources marines (Caddy and Cochrane, 2001; Yellen et al., 1995). Durant des siècles, ils ont pu exploiter en libre accès ces ressources qu'ils considéraient alors comme inépuisables (Cushing, 1988; Huxley, 1883; Lackey, 2005). A mesure que les méthodes de pêche devenaient de plus en plus performantes, les pêcheries mondiales se développèrent et poursuivirent leur essor vers la haute mer (Pauly et al., 2003). Au cours du 20ème siècle, les inquiétudes pour l'état des stocks et les écosystèmes marins grandirent. Ce fut le siècle d'une irrésistible expansion des pêcheries mondiales, sous l'impulsion d'une demande croissante en poisson et de la volonté des Etats d'étendre leur influence sur les océans (Santos, 2000). Avec l'augmentation de l'effort de pêche, les premiers effondrements de pêcheries se produisirent (e.g. Hannesson, 1996; Pauly et al., 2002), attirant sur la dégradation de l'état des ressources marines. Bientôt, des messages alarmistes pour le futur des écosystèmes marins furent émis par la communauté scientifique (Worm et al., 2006) et abondamment relayés par les médias. C'est encore le cas aujourd'hui. Cette crise mondiale a eu de profondes répercussions sur les modes d'évaluation et de gestion des pêcheries, ainsi que sur la perception du grand public de la pêche et des pêcheurs. Elle a stimulé l'émergence de nouveaux concepts tels que l'Approche Ecosystémique des Pêches (AEP, Garcia, 2003; Pikitch et al., 2004) ou l'application du Principe de Précaution aux pêcheries mais il reste encore beaucoup à faire pour résorber les problèmes de surcapacité (Greboval and Munro, 1999) et de surexploitation que traversent nombre de pêcheries. La situation est particulièrement complexe pour les pêcheries de la haute mer, du fait de la multiplicité des acteurs et des pêcheries qui les exploitent, et les pêcheries thonières tropicales à la senne en sont un parfait exemple. Au cours des années récentes, elles ont été de plus en plus pointées du doigt, du fait de leur utilisation des Dispositifs de Concentration de Poissons (DCP), des objets artificiels dérivants spécifiquement dédiés à l'agrégation et à la pêche des thons tropicaux.

De nombreuses espèces de poissons présentent un comportement d'agrégation avec les objets flottants à la surface de l'océan. Ce comportement des poissons est connu et utilisé par les pêcheurs depuis longtemps puisqu'il leur permet d'augmenter leur succès de pêche et de diminuer le temps dédié à la recherche aléatoire des bancs de poissons (Fréon and Dagorn, 2000). En 1964, lorsque la pêche thonière commence dans l'Océan Atlantique tropical, l'utilisation des objets flottants s'appuie sur les objets naturels et les débris des activités humaines apportés par les courants et accumulés dans les zones de convergence océanique. Cette pratique reste limitée au cours des premières décennies de cette pêcherie (Fonteneau et al., 2013). Il faudra attendre le développement de la pêcherie dans l'Océan Indien pour qu'elle prenne un essor considérable. A partir des années 1990, les DCP dérivants, généralement constitués d'un radeau en bambou et de morceaux d'anciens filets de pêche, sont décrits comme une solution viable pour atteindre la pleine exploitation des stocks de thons tropicaux – notamment du listao – et la profitablité économique de la pêcherie. La littérature scientifique les décrits alors comme un outil prometteur pour capturer les bancs trop rapides (Bard et al., 1985) ou trop profonds (Ariz et al., 1999) qui posent alors problème aux senneurs.

A la fin des années 1980 et au début des années 1990, l'utilisation des DCP prend de l'ampleur. Des balises radio à la fin des années 1980 et des balises GPS une décennie plus tard (Castro et al., 2002; Fonteneau et al., 2013) sont développées pour suivre la trajectoires des DCP au cours de leur dérive. Les moyens technologiques à disposition des senneurs deviennent de plus en plus performants (Torres-Irineo et al., 2014). Les navires d'assistance, en charge de baliser des objets flottants pour les senneurs et de détecter les bancs de thons associés à des objets flottants (Fonteneau et al., 2000) font leur apparition. A mesure que l'utilisation des DCP s'intensifie, les inquiétudes pour les stocks de thons, les prises accessoires (espèces non ciblées par les senneurs) et le fonctionnement des écosystèmes grandissent (Ariz et al., 1999; Fonteneau et al., 2000; Hallier et al., 1992). Sur le plan des fonctionnement des écosystèmes, les DCP contribuent à plus de prises accessoires (Amandè et al., 2008, 2010), à des captures fantômes de requins (Filmalter et al., 2013) et de tortues, à des destructions d'habitat par le biais d'échouages (Maufroy et al., 2015) et un possible piège écologique. L'augmentation rapide du nombre de DCP pourrait piéger les thons dans des zones qui ne seraient pas optimales pour leur alimentation (Ménard et al., 2000), leur reproduction et pourrait affecter leurs migrations naturelles (Marsac et al., 2000). L'utilisation des DCP pose également des questions importantes d'évaluation et de gestion des stocks. L'efficacité des senneurs est très largement modifiée par cette utilisation des DCP puisqu'ils contribuent entre autres à réduire le temps passé à rechercher aléatoirement des bancs de thons. Ces modifications sont mal prises en compte par les méthodes classiques d'estimation de l'effort de pêche (les moyens mis en œuvre pour capturer du poisson), qui reposent sur le temps de recherche des bancs ou le temps en mer (Fonteneau et al., 2013; ISSF, 2012). Malgré l'importance de cet indicateur, la mesure de l'effort de pêche des senneurs est donc difficile.

Malgré l'importance de l'utilisation des DCP et la pression grandissante pour l'établissement de mesures de gestion, beaucoup de questions se posent encore sur les modalités d'utilisation des DCP et des objets balisés au sens large (DCP et objets naturels). Quand, comment et où sont-ils mis à l'eau? Combien d'entre eux dérivent actuellement dans les océans Atlantique et Indien? Comment cela affecte-il l'efficacité de pêche des thoniers senneurs tropicaux? Pour répondre à ces questions, 3 objectifs sont proposés pour cette thèse :

i- comprendre les modalités d'utilisation des DCP et des objets balisés (stratégies de mise à l'eau, nombre de DCP, etc).

ii- mesurer l'efficacité de pêche des senneurs, en lien avec l'utilisation des DCP et des balises GPS ainsi qu'avec l'utilisation des navires auxiliaires

iii- explorer la perception des différentes parties prenantes des impacts de la pêcherie et évaluer les modalités de sa gestion

B- Dynamique à grande échelle de l'utilisation des objets flottants dans les Océans Atlantique et Indien

Pour la première fois, les trois armements français opérant dans les océans Atlantique et Indien ont mis à la disposition de l'IRD les positions des balises GPS qui servent à suivre les DCP dérivants de la flotte de senneurs français. Cette source d'information comprend un mélange de positions « en mer » (lorsque la balise GPS équipe un objet flottant dérivant en mer) et « à bord » (lorsque la balise GPS est allumée sur le pont du senneur pour s'assurer de son fonctionnement). Le premier chapitre de cette thèse décrit le travail de séparation de ces deux états, au cours duquel différentes méthodes de classification ont été testées et comparées. Dans un second temps, les positions en mer sont utilisées pour décrire la dynamique des objets flottants balisés par la flotte française dans les océans Atlantique et Indien.

Toutes les méthodes de classification testées nécessitent la constitution préalable d'un jeu de données d'apprentissage. A l'aide des positions GPS et des positions VMS, les trajectoires des balises et des senneurs ont été reconstituées. Une partie de ces deux types de trajectoires a été superposée pour l'année 2009 afin de détecter les portions de trajectoire communes. Pour ces 103 trajectoires, des paramètres décrivant chacune des positions comme la vitesse ou le changement de direction ont été calculés. Quatre modèles de classification ont été construits et comparés en utilisant cet échantillon d'entrainement : un filtre de vitesse (VEL), un modèle de régression logistique multiple (MLR), un réseau de neurones artificiels (ANN) ainsi qu'un modèle de Random Forest (RF). Elles ont été choisies soit pour leur caractère intuitif (VEL, MLR) soit pour leur flexibilité (ANN et RF), soit leur capacité à gérer des jeux de données complexes (ANN, RF) et potentiellement bruités (RF). Afin de comparer les performances des modèles entre elles, le jeu de données d'apprentissage a été aléatoirement séparé 100 fois en un jeu de données d'entraînement et un jeu de données de validation contenant chacun 50% des trajectoires déjà classées. Les 100 jeux de données d'entraînement ont servi à calibrer les paramètres de chacun des modèles par une procédure de bootstrap (200 itérations) utilisée pour éviter les problèmes surajustement.

Les 100 jeux de données de validation ont servi à la comparaison des performances des modèles de classification calibrés par la procédure de bootstrap. Les classes prédites par les modèles ont été comparées aux classes obtenues par superposition des trajectoires des balises et des senneurs pour calculer 4 indicateurs basés sur la matrice de confusion : l'exactitude (taux d'erreur), la précision, le Taux de Vrais points en Mer et le Taux de Faux points en Mer. Tous les modèles de classification ainsi construits font l'hypothèse forte d'une indépendance entre les positions successives d'une balise GPS au cours du temps ce qui n'est évidemment pas le cas et peut conduire à des transitions entre états d'une même balise impossibles dans la réalité. Pour évaluer ce risque, un dernier indicateur basé sur les trajectoires a été calculé. Le taux de segmentation des trajectoires évalue le nombre moyen de séquences du type en mer - à bord - en mer et à bord - en mer - à bord par trajectoire. Le meilleur modèle de classification, un modèle Random Forest a été choisi sur la base de ces cinq indicateurs de performance. Pour en améliorer encore les performances, une correction des sorties du modèle a été testée. Elle vise à corriger les séquences du type à bord - n fois en mer - à bord qui semblent peu probables lorsque le nombre n de répétitions de positions en mer est faible. A l'aide du taux d'erreur et du Taux de Faux points en Mer, le nombre optimal de positions en mer à corriger a été déterminé.

Dans une seconde partie, les positions de balises en mer ont été utilisées entre 2007 et 2011 pour fournir des informations simples sur la dynamique d'utilisation des objets flottants balisés par les senneurs français. Entre autres, elles permettent d'estimer le temps en mer des DCP (ou plus précisément le temps qu'une balise GPS donnée passe sur un DCP dérivant en mer), avec une moyenne de 48 jours environ dans l'Océan Atlantique et 37 jours dans l'Océan Indien. La saisonnalité des temps et des distances en mer est également décrite et montre par exemple dans l'Océan Indien que les temps en mer sont plus courts de Mars à Avril et d'Août à Septembre lorsque la pêche sur DCP est la plus intense. Une partie conséquente des objets équipés par la flotte française dérive hors des zones de pêche, conduisant à un « effort de pêche fantôme » et dans 10% des cas à un échouage de l'objet flottant. Ces échouages pourraient avoir des impacts importants sur des habitats fragiles comme les écosystèmes coralliens des Maldives, des Chagos ou des Seychelles.

C- Estimation de l'augmentation massive de l'utilisation des objets flottants utilisés par les thoniers senneurs dans les océans Atlantique et Indien

L'analyse préliminaire de l'information contenue dans les positions des balises GPS françaises et dans les autres sources d'information montre une grande variabilité dans les modes d'utilisation de ces balises sur les DCP et les objets naturels. Pour combiner ces données complexes et variables, nous avons fait appel aux connaissances des patrons pêcheurs. 14 d'entre eux ont accepté d'échanger autour de leurs pratiques avec les DCP et les objets flottants balisés. Ces entretiens nous ont permis de collecter de l'information qualitative qui a servi à guider les analyses statistiques des données quantitatives (Johannes et al., 2000; Moreno et al., 2007; Neis et al., 1999) disponibles pour ce travail. Entre autres, les entretiens avec les patrons pêcheurs nous ont permis d'identifier deux facteurs importants pour prendre la décision de mettre un nouvel objet à l'eau : l'utilisation de zones et de saisons ainsi que celle des courants. Sur la base de cartes de densité de moyennes mensuelles mise à l'eau des balises GPS françaises entre 2007 et 2013 (obtenues par la méthode de classification du chapitre 1), une méthode de classification hiérarchique a été utilisée pour identifier les saisons de mise à l'eau des balises GPS sur les objets flottants.

Dans chaque océan, 4 saisons ont été identifiées. Dans l'Océan Atlantique, les mises à l'eau se sont progressivement déplacées du Golfe de Guinée au Sénégal entre Janvier et Mars. De Juin à Septembre, les mises à l'eau se sont progressivement déplacées vers le Sud Est de l'Océan Atlantique, en occupant une zone au large du Gabon, avant de se déplacer à nouveau vers le Golfe de Guinée d'Octobre à Décembre. Dans l'Océan Indien, les mises a l'eau ont commencé de Mars à Mai dans le Canal du Mozambique avant de remonter vers le Nord Ouest des Seychelles de Juin à Juillet et de rejoindre la zone Somalienne pour la principale saison d'utilisation des DCP d'Août à Octobre. La fin de l'année est marquée par une diminution de l'intensité des mises à l'eau lorsque les senneurs se déplacent vers la zone Sud Est des Seychelles de Novembre à Février. Ces saisons de mise à l'eau ont été très fortement reliées aux courants. Dans l'Océan Atlantique, elles visent principalement à éviter les forts courants d'Ouest qui transportent les objets hors des zones de pêche. Dans l'Océan Indien, les comportements changent en fonction des courants saisonniers, avec soit une utilisation des courants lorsque l'upwelling somalien se met en place, soit un évitement des forts courants d'Est en fin d'année. Les mises à l'eau se font également sur des zones et à des saisons similaires aux zones et aux saisons de pêche chez les Français. La corrélation entre les deux types d'activité est testée en tenant compte de l'auto-corrélation spatiale.

Dans un second temps, le nombre de DCP et de balises utilisés sur des DCP et des objets naturels dans les océans Atlantique et Indien a été estimé. La donnée balise GPS française ne nous donne accès qu'à l'information concernant la flotte française de senneurs, alors que d'autres flottes (espagnole, asiatiques par exemple) utilisent tout autant voire plus de balises GPS que les navires français. D'autre part, si l'on souhaite avoir uniquement accès aux objets flottants directement liés aux navires de pêche, il faudrait pouvoir séparer les objets naturels de ceux mis à l'eau par les pêcheurs, c'est-à-dire des DCP. Cette information a donc été combinée aux données collectées par les observateurs embarqués à bord des senneurs Français et Espagnols de 2007 à 2013, afin d'estimer les proportions de balises Françaises, Espagnoles ou autres, ainsi que les proportions d'objets naturels ou de DCP sur une grille de résolution 1°. Sur une zone de 1°, les nombres de balises Françaises, Espagnoles ou Autres correspondent à des tirages dans une loi multinomiale. La distribution des proportions de de balises Françaises, Espagnoles ou Autres ont été estimés par une approche

MCMC (package R metrop, utilisant l'algorithme de Metropolis-Hastings). Les résultats indiquent une forte progression dans l'utilisation des DCP balisés par toutes les flottes entre 2007 et 2013, qui est multipliée par 7.0 et 4.2 dans les Océans Atlantique et Indien respectivement. Une nouvelle fois, les résultats indiquent l'existence d'une saisonnalité dans le nombre de DCP et d'objets balisés, qui correspond aux saisons de mise à l'eau et de pêche identifiées précédemment. Cette augmentation massive du nombre de DCP et de la densité de balises GPS suggère une forte modification des habitats pélagiques ainsi que des modifications dans les stratégies et l'efficacité des thoniers senneurs, qui sont examinées dans le chapitre 3.

D- Contribution des navires auxiliaires et des DCP à l'efficacité de pêche des thoniers senneurs tropicaux européens des océans Atlantique et Indien

L'effort de pêche est un indicateur clé pour l'évaluation et la gestion des stocks de thons tropicaux des océans Atlantique et Indien. Traditionnellement, il est mesuré en tenant compte du temps de recherche aléatoire des bancs de poissons. Mais dans le cadre de la pêche sous DCP, cette approche est inappropriée. En effet, l'utilisation des objets flottants permet entre autres de diminuer le temps de recherche aléatoire des bancs de thons tropicaux, en augmentant la probabilité de les détecter. Mesurer l'effort de pêche utilisant des DCP, et plus généralement des objets flottants suivis par GPS requiert donc une méthode adaptée, qui tienne compte de l'utilisation de ces objets. Du fait de l'utilisation de plus en plus importante des DCP, l'efficacité de pêche des senneurs augmente rapidement. Elle est liée aux caractéristiques techniques des senneurs (leur taille ou leur capacité de stockage du poisson par exemple), aux méthodes de détection du poisson ainsi qu'aux techniques de pêche utilisées (Le Gall, 2000). Les DCP contribuent à l'augmentation de cette puissance de pêche par deux mécanismes. D'abord parce qu'ils servent de moyen de détection du poisson, en réduisant le temps passé à chercher aléatoirement des bancs de thons (Fréon and Dagorn, 2000; Le Gall, 2000), en utilisant directement les DCP, ou avec le support des navires auxiliaires, dont le rôle est aussi de signaler au senneur la présence de poisson sous les DCP ou la présence de Bancs Libres sur une zone donnée. Ensuite, parce qu'ils servent d'outil de pêche du poisson en contribuant à son agrégation, ce qui permet de diminuer les risques d'échappement du banc lors de sa capture (Fréon and Dagorn, 2000).

Dans ce chapitre, les données des livres de bord des senneurs Français et Espagnols des océans Atlantique et Indien, ainsi que les caractéristiques techniques des senneurs et leur collaboration avec les navires d'assistance (uniquement pour l'Océan Indien) ont été utilisées. Dans un premier temps, ces données ont été utilisées pour mesurer les changements de stratégie des senneurs avec les objets flottants (définies comme la proportion de coups de pêche sur DCP sur le moyen terme, i.e. à l'échelle du mois) en fonction de l'année, du mois, de la taille des senneurs, de leur flotte d'appartenance et de leur utilisation des navires auxiliaires, à l'aide de modèles linéaires généralisés. Les résultats indiquent une progression de la stratégie DCP entre 2003 et 2014, la proportion de coups de pêche sur objet flottant augmentant de 41.8% en 2003 à 59% en 2014 dans l'Océan Atlantique et de 50.9% à 70.6% dans l'Océan Indien. Les résultats indiquent également que les plus grands senneurs, les senneurs Espagnols, et les senneurs travaillant en collaboration avec un navire auxiliaire ont une stratégie plus clairement tournée vers les objets flottants que les autres.

Dans un second temps, l'effet de la taille des senneurs, de leur flotte d'appartenance, de leur utilisation des navires auxiliaires et de leur stratégie avec les DCP sur l'efficacité des senneurs a été évaluée à l'aide de modèles linéaires généralisés mixtes (GLMM). Cinq dimensions de l'efficacité des thoniers senneurs ont été prises en compte dans cette analyse : la capture par jour (CPUE1), la capture par calée (CPUE2), la capture rapportée à la distance parcourue (CPUE3), le nombre de coups de pêche par jour (SPUE) et finalement la distance parcourue par jour (DPUE). Les résultats indiquent que les plus grands senneurs, les senneurs Espagnols et les senneurs bénéficiant d'un navire auxiliaires sont les plus efficaces. Les navires auxiliaires contribuent par exemple à une augmentation de l'efficacité des senneurs de 12.3% à 15.3% selon la mesure d'efficacité considérée. De la même façon, l'efficacité des senneurs augmente lorsque la proportion de coups de pêche sur objet qu'ils réalisent augmente.

Dans un dernier temps, ces résultats ont été utilisés pour construire un indice d'efficacité de la flotte de thoniers senneurs Européens entre 2003 et 2014. L'efficacité de la flotte a été décomposée en deux termes: une efficacité technique qui mesure les changements liés aux caractéristiques des senneurs (leur taille et leur flotte d'appartenance) ainsi que leur utilisation des navires auxiliaires et une efficacité technique qui prend en compte leurs stratégies avec les objets flottants. Les résultats montrent une progression de l'efficacité totale des flottes de senneurs à un rythme de 0.3% à 1.5% par an dans l'Océan Atlantique et 0.9% à 2.2% dans l'Océan Indien, selon la mesure d'efficacité considérée. Entre 2003 et 2014, l'efficacité stratégique a progressé de 8.7% à 15.5% dans l'Océan Atlantique et entre 6.5% et 15.4% dans l'Océan Indien selon l'indice d'efficacité. En termes d'efficacité technique, on note une progression allant de 3.9% à 18.2% selon l'océan et la dimension d'efficacité considérée.

E- Prise en compte des connaissances scientifiques et des connaissances des pêcheurs pour une meilleure gestion de l'utilisation des objets flottants : le cas de l'Océan Indien

L'objectif principal de cette thèse était de mieux comprendre l'utilisation des objets flottants par les thoniers senneurs tropicaux à l'aide se multiples sources d'information : les positions GPS des DCP et des objets naturels français, les informations collectées par les observateurs embarqués, les livres de bord ou encore les données VMS. La pêcherie a été suivie depuis son développement et une très grande quantité de connaissances scientifiques était disponible pour guider les analyses des ces données. Cependant, un partie des ces connaissances avaient été acquises il y a plus de 20 ans, à l'image des saisons de mise à l'eau des DCP (p.ex. Ariz et al., 1999) et la pêche sur objet flottant entrait à nouveau dans une phase de profonds changements, en raison de l'augmentation rapide de l'utilisation des DCP et des balises GPS. Les connaissances des pêcheurs, qui sont les premiers témoins de ces changements, peuvent être inestimables pour identifier des informations cruciales, éviter des formuler des hypothèses aberrantes ou même pour accélérer la compréhension du fonctionnement d'une pêcherie.

Depuis le développement de la pêcherie, les pêcheurs ont régulièrement échangé avec les scientifiques sur le comportement du poisson (Moreno et al., 2007), les changements technologiques (Gaertner et al., 2000; Lopez et al., 2014), leurs stratégies de pêche (Guillotreau et al., 2011) ou la gestion de la pêcherie (Davies et al., 2015). Le chapitre 4 apporte une contribution supplémentaire à ces approches, en combinant les connaissances scientifiques et les connaissances des capitaines de senneurs pour mieux comprendre l'utilisation des objets flottants et comparer les options de gestion de la pêcherie. Ce travail a été mené en deux temps, avec une premier groupe d'entretiens semi-directifs en 2013, qui visait à guider le travail avec les sources de données quantitatives disponibles à l'IRD et un second groupe d'entretiens réalisés en 2015 qui visait à comprendre les perceptions des pêcheurs sur les impacts et la gestion de la pêcherie, en s'appuyant sur les résultats de cette thèse.

En 2013, les entretiens avec les patrons pêcheurs nous ont permis par exemple permis d'identifier deux facteurs importants pour prendre la décision de mettre un nouvel objet à l'eau : l'utilisation de zones et de saisons ainsi que celle des courants. Ces deux éléments ont été analysés dans la donnée des positions de balises GPS françaises dans le chapitre 2. En 2015, les résultats obtenus au cours de la première phase de l'étude ont été présentés aux patrons pêcheurs au cours de 15 nouveaux entretiens au cours desquels, leur perception des impacts de la pêcherie (pour les thons tropicaux, les prises accessoires et le fonctionnement général des écosystèmes) a été abordée, afin de formuler des propositions de gestion de ces impacts et de la pêcherie. Les entretiens révèlent entre autres les raisons de l'augmentation rapide du nombre de DCP et de balises GPS estimée dans le chapitre 2, qui reposent fortement sur une compétition accrue avec certains senneurs Espagnols ayant développé une stratégie très efficace basée sur l'utilisation d'un grand nombre d'objets flottants. Ils indiquent une potentielle course au poisson dans les années récentes, du fait d'un manque de gestion spécifique des problématiques liés aux objets flottants. Les entretiens révèlent également des préoccupations grandissantes des capitaines français en lien avec l'augmentation du nombre de DCP qui pourrait modifier le comportement des thons tropicaux par des mécanismes de fractionnements des bancs (Sempo et al. 2013), une instabilité des bancs des bancs sous les objets flottants, ou une disparition des bancs libres (notamment de listaos). Ils montrent la nécessité d'améliorer la gestion existante de la pêcherie en remettant en question la décision récente des ORGP thonières (CICTA dans l'Atlantique et CTOI dans l'Océan Indien) de limiter l'utilisation des balises GPS à 550 par jour et par bateau et les achats de balises à 1100 par an et par bateau. Outre des difficultés de suivi du nombre de balises GPS actives, les patrons suggèrent un effet pervers de cette limitation peu restrictive qui pourrait conduire certains senneurs à augmenter leur nombre de balises GPS alors que d'autres ne modifieraient que très légèrement leurs stratégies. Une gestion efficace pourrait passer par des décisions complémentaires de réduction de la capacité des flottes de senneurs ou la mise en place de quotas (en tenant compte des autres engins de pêche dans ces mesures), ainsi que par un meilleur suivi des activités des navires auxiliaires.

F- Discussion générale

Cette dernière partie dresse un bilan des connaissances acquises pendant ces travaux de recherche : le développement d'une méthode de traitement des trajectoires de balises GPS (chapitre 1) qui est aujourd'hui utilisée en routine par l'IRD pour traiter les données fournies par les armements français l'identification des zones et des saisons de mise à l'eau des balises GPS, l'estimation du nombre de DCP et de balises GPS utilisés par toutes les flottes dans les Océans Atlantique et Indien, l'estimation de la contribution des objets flottants et des navires auxiliaires à l'efficacité de pêche des thoniers senneurs tropicaux et finalement l'identification des quotas, des limitations de capacité ou un meilleur suivi des navires auxiliaires pour améliorer la gestion de la pêcherie. Ces résultats s'appuient à la fois sur une grande quantité d'information diverses et sur des approches transdisciplinaires.

Ils contribuent à une meilleure compréhension de l'utilisation des DCP et des objets flottants au sens large, depuis leur mise à l'eau jusqu'à la fin de leur utilisation en mer. Ces informations sont nécessaires pour lever les doutes qui subsistent sur les impacts réels de l'augmentation du nombre de DCP et de balises GPS quant à la pression exercée sur les stocks de thons tropicaux, l'altération du comportement naturel des thons, les prises fantômes ou la destruction d'habitats vulnérables. Ces résultats doivent cependant être vus comme une première étape vers l'acquisition de ces connaissances du fait du manque d'informations détaillées sur l'utilisation des balises GPS par les flottes des senneurs Espagnoles en autres et des changements rapides dans les stratégies des senneurs qui nécessite un suivi constant des modifications de leur comportement avec les objets flottants. Cependant, être en mesure d'estimer le nombre de DCP dérivants dans les océans Atlantique et Indien est une étape considérable pour améliorer le suivi de la pêcherie.

De la même façon, le suivi de l'effort de pêche et de l'efficacité des senneurs est nécessaire à une meilleure évaluation et une meilleure gestion des stocks de thons tropicaux. Jusqu'à présent, en l'absence d'une mesure d'effort adaptée aux senneurs et à leur utilisation massive des objets flottants, les CPUE des senneurs n'ont pas pu être utilisées par les ORGP thonières. Un des objectifs initiaux de cette thèse était de proposer une mesure d'effort sous objet flottant, en séparant les activités sur banc libre et sur objet. Ces deux modes de pêche n'étant pas séparés dans le temps et l'espace, ce travail n'a pas pu être mené à bien. Néanmoins, même en l'absence d'une mesure d'effort de pêche, qu'elle soit nominale ou effective, il reste possible d'envisager des indices d'abondance alternatifs, qui reposeraient sur les données enregistrées par les balises échosondeurs des objets flottants. L'absence d'une mesure d'effort de pêche ne doit pas non plus empêcher le suivi des évolutions dans l'efficacité de pêche des senneurs. Ce suivi requiert les mêmes données (livres de bord, caractéristiques techniques des navires, etc) et les mêmes approches statistiques (GLM, GLMM, etc) que celles qui sont utilisées pour standardiser les CPUE et dériver un indice d'abondance des stocks de thons tropicaux. Il pourrait donc être nécessaire de conduire ces analyses lors des groupes de travail des ORGP thonières.

Enfin, la discussion de cette thèse revient sur les options de gestion pour la pêcherie sous objet flottant, dans un contexte grandissant de pression de la part des ONG environnementales, qui suggèrent l'abandon pur et simple de cette pratique de pêche. Cette proposition pourrait ne pas être la bonne, en particulier si elle devait avoir des répercussions économiques trop importantes ou augmenter la pression de pêche exercée sur des stocks d'albacore déjà surexploités. Elle montre néanmoins la nécessité de mieux gérer la pêcherie, qui passe d'abord par une meilleure collecte des informations nécessaires à son suivi : les positions des balises GPS de toutes les flottes (détaillées ou agrégées sur une échelle fine, comme par exemple celle du mois) ou encore les liens entre senneurs et navires auxiliaires pour mesurer la contribution des navires auxiliaires à l'effort de pêche des senneurs. L'amélioration de la gestion de la pêcherie passe également par une réflexion approfondie sur les modalités de cette gestion. La mise en place de plans de gestion des DCP ainsi que la limitation de leur utilisation depuis 2015 sont des étapes encourageantes. Elles nécessitent aujourd'hui des décisions complémentaires, bien que difficiles à prendre et qui viseraient à réguler l'effort ou les captures.

GENERAL INTRODUCTION

1. 1. Challenges for the world fisheries

1.1.1. When too many fishermen chase too few fish

Humans have long relied on marine resources (Caddy and Cochrane, 2001; Yellen et al., 1995). For thousands of years, until the human population grew and technological means to exploit these resources improved, the ocean was considered as an inexhaustible source of food and wealth for humankind. The principle of “Freedom of the Seas” granted open access to ocean resources that were seen as limitless. As long as exploiting the seas remained a matter of subsistence for small communities of fishers with moderately effective fishing gears, these perceptions remained the dominant paradigm (Huxley, 1883; Cushing, 1988; Lackey, 2005). As fishing gears and techniques improved and fisheries developed and caught increasing amounts of fish in further and further distant waters, these assertions were progressively abandoned (Pauly et al., 2003). By the 1850s, the increasing fishing pressure had already contributed to severe declines of fish stocks in several locations of the world (Royce, 1988; Lear, 1998; Smith, 2002). For some time, the question of knowing whether these fish declines could be attributed to environmental changes or to the effects of the increased fishing pressure remained the subject of intense debates (Schaefer, 1957; Caddy, 1999).

The 20th century saw the emergence of unprecedented concerns regarding the impacts of fishing on the decline of fish stocks. By the 1950s, there were evidence that the absence of regulation of fisheries could lead to a race for fish (Hardin, 1968) and to overexploitation (Schaefer, 1957). Because fish stocks are common pool resources, open access to fisheries had already encouraged a competition between fishers to get the larger share of the catch. To further increase their benefits and make sure to catch more fish than the others, fishers had invested in larger and more powerful vessels. With these investments, the fishing effort (i.e. the means deployed by a fishing fleet to catch fish, e.g. number of fishing days) and the fishing capacity (i.e. the means available for a fishing fleet to catch fish, e.g. the carrying capacity of fishing vessels) had increased, leading to various cases of overexploitation. In these typical situations of ‘tragedy of the commons’ (Hardin, 1968), there were simply too many fishermen chasing too few fish.

In response to these concerns of reduced abundance, science-based management of fisheries developed. Mathematical models treating fish as renewable resources were improved (e.g Beverton and Holt, 1957; Schaefer, 1957) and used to conduct single stock assessments. These models, that are still the basis of current assessment of fish resources, assume that each stock has the potential to produce a surplus that is linked to fishing effort. Provided a certain level of fishing effort, and under stable conditions, it would be possible to exploit a stock indefinitely (Schaefer, 1957). In theory, these models can even be used to define an optimal level of fishing effort to exploit this surplus production, for example to reach the Maximum Sustainable Yield (MSY) or the Maximum Economical Yield (MEY). At this stage, the political and economic objectives of fisheries management were then to maximize the production of food and the socio-economic return of fishing activities on the long term (Lackey, 2005; Schaefer, 1957). However, this paradigm of efficient use of fish populations was soon challenged by insufficient consideration of the entire ecosystem and pressures for the development of fisheries (Botsford et al., 1997).

Right after World War II, fishers were asked to participate in the effort of sustaining the economic growth and feeding the world (Caddy and Cochrane, 2001; Royce, 1988). This was the time of the expansion of world fisheries to meet the fast increasing demand for fish and the will of States to expand their influence on the oceans (Santos, 2000). The world population grew and fishing production grew even faster (FAO, 2014; Pauly et al., 2002; Royce, 1988) supported by open access to fisheries and ever more efficient fishing technologies and progressive globalization. The early successes of the development of the world fisheries further stimulated their development (Pauly et al., 2002), often supported by subsidies to compensate for the initial signs of depletion, which in turn led to a global problem of overcapacity (Caddy and Seijo, 2005). Fishing fleets expanded from their traditional fishing grounds to foreign and high seas fishing grounds (Christy and Scott, 2013) with the support of fishing agreements (Le Manach et al., 2013).

Following this increasing fishing pressure, spectacular collapses occurred for Norwegian herring during the 1960s and a decade later in the North Sea (Dickey-Collas et al., 2010; Lorentzen and Hannesson, 2004), the Peruvian anchovy fisheries in the early 1970s (Pauly et al., 1998) and for the North Eastern Atlantic cod during the late 1980s – early 1990s (Hannesson, 1996; Myers et al., 1997), raising awareness on global concerns for the sustainability of fisheries. Soon, alarming messages regarding the state of marine ecosystems were spread by the scientific community (e.g. Pauly et al., 1998 ; Hutchings, 2000; Myers and Worm, 2003). Pessimistic assertions, sometimes distorting and over interpreting the initial message of scientific publications, were conveyed. A famous example of this is the publication of Worm et al. (2006) that predicted the collapse of all fish stocks by 2048 if current catch trends continued. This statement, that was originally only a minor conclusion of their work and has been subject to criticism (Branch, 2008), has been making the headlines for the two last decades. The still ongoing fisheries crisis caused profound changes in fisheries science and management, as well as in the perception of fishers and fisheries by the public (Beddington et al., 2007). They gave rise to new concepts in fisheries science and management, such as the Precautionary Approach or the Ecosystem Approach to Fisheries (Garcia, 2003; Pikitch et al., 2004) but so far did not solve the problems of excess capacity and excess fishing effort experienced by many fisheries around the world.

Since the 2000s, the debate continues between those who argue that none of the challenges faced by fisheries have been appropriately addressed (Pauly et al., 2002, Cullis-Suzuki and Pauly, 2010) and those who advocate that the situation is gradually improving (Beddington et al., 2007; Hilborn, 2007; Worm et al., 2009). Yet, more than 60 years after the dramatic rise of industrial fisheries, some of the very questions that led to the global fisheries crisis are still unanswered. In particular, what level of fishing effort is exerted and can be sustained? Which management options, accounting for ecosystem functioning as well as for fishers behaviour, can be considered? In many cases, answering these questions remains a tremendous challenge. The lack of information that would serve as basis to measure fishing effort and design effective management tools, the insufficient integration of all aspects of fisheries systems (biological, social, economical, political) and the multiplicity of stakeholders (fishers, fishing companies, managers, fisheries scientists, politics, NGOs) do not simplify the task of fisheries managers. As fisheries play an important role in food security, employment and wealth for millions of human beings (FAO, 2014), questions of sustainability of the world fisheries remain as important as ever.

1.1.2. Ever further into the sea: fishing in distant waters

Throughout this dramatic rise of world fisheries, fishermen have left their traditional fishing grounds to exploit marine resources in distant waters. This was true when stories of miraculous cod catches attracted the first Europeans off Newfoundland during the 16th century (Lear, 1998) and this is still true for modern tropical tuna fisheries (Le Manach et al., 2013). For several centuries, States had virtually no interest in these distant water fisheries. The priority was to ensure safe and even exclusive access to trading and navigation routes. From the 17th century to 1982, the concept of “Freedom of the Seas” applied to all activities in the ocean including trading and fishing. Everyone had the right to exploit common fish resources and no one had the right to exclude the others from fishing grounds. Terrestrial waters generally extended no further than 3 nautical miles. As long as open access to fisheries remained the dominant paradigm, this inevitably led to the overexploitation of fish stocks (Hardin, 1968). There was not only a competition between fishers to catch more fish than the others but also between States to get the largest share of catches. Even when there were evident signs of depletion, the priority was given to the preservation of short-term national interests. In the absence of international agreements, there was no incentive to reduce national catches and effort if the other States did not make similar decisions.

During the 20th century, the competition for the control of the oceans increased. But once again, it was not only the fate of marine resources that was at stake (Royce, 1988; Grzybowski et al., 1995). Soon, the prospect of the massive resources that the seas had to offer (fish, oil, ore), the ever improving technology to exploit these immense resources, and the competition to maintain a military presence in the world oceans became sources of tensions (Kedziora, 1997). One by one, several countries unilaterally decided to expand their terrestrial waters. The United States extended their jurisdiction on the resources of their continental shelf in 1945. After World War II, they were soon followed by several countries extending their territorial sea from 3 to 12 nautical miles. Several others claimed sovereignty over a 200 nautical mile zone (Eckert, 1979; Jennings et al., 2009). Unilateral decisions of States to protect what they saw as “their” resources resulted in resentment and fishing disputes between local and distant water fleets (Kedziora, 1997; Jennings et al., 2009). These fishing disputes further underlined the need for a revision of the international Law of the Sea (LOS).

The demand of States for an exclusive jurisdiction over areas adjacent to their coasts was reiterated several times. Neither the Hague Conference of 1930 nor the Geneva Convention on the High Seas of 1958 provided the desired answers to these claims (Grzybowski et al., 1995; Jennings et al., 2009). But during the early 1970s, fishing nations entered the final negotiation phase leading to the establishment of Economic Exclusive Zones (EEZs, Figure 1.1). Since the 3rd UN Convention on the Law of the Sea (UNCLOS III) in 1982, coastal states have sovereign rights for managing and exploiting all types of natural resources (living or non-living) within their 200 nautical miles EEZs (UNCLOS, 1982). This does not mean that coastal states benefit from sovereign ownership of these resources but that they have exclusive authority on the rules that apply within their EEZs. Among others, they are in charge of the determination of quotas within these zones and set the rules allowing third countries to fish within their EEZs (Bjørndal et al., 2000). As an immediate consequence of the new LOS, 90% of the world catches ended up under national control and catches of distant water fleets decreased. Small coastal states that did not possess large and powerful fishing fleets now had the control of important fish resources (Bjørndal et al., 2000; Jennings et al., 2009). Soon, as many of these coastal states could not “harvest the entire allowable catch” within their EEZs, fishing agreements were signed with distant water fleets (e.g. European Union, Russia and various Asian fleets, Le Manach et al., 2013). Distant water fleets were therefore allowed to fish within EEZs of various coastal countries against a monetary compensation (e.g. European Union purse seiners in Seychelles). Though these fishing agreements are not always advantageous for coastal countries (Le Manach et al., 2013), this was not the only limitation of UNCLOS.

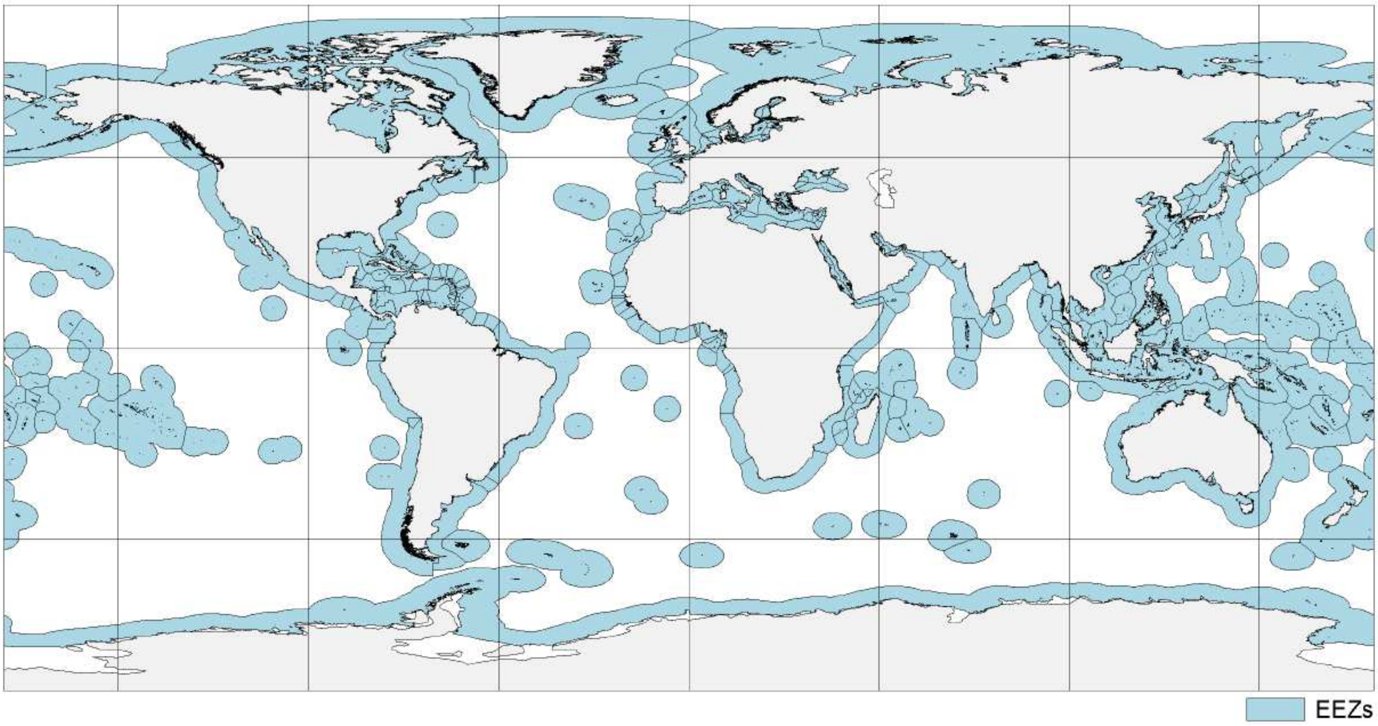


Figure 1.1: Exclusive Economic Zones (EEZs) of the world. EEZs cover the area between the coastline to 200 nautical miles (370 km) representing 40% of the world oceans (source: VLIZ, 2014)

As fish do not respect man-made boundaries (Bjørndal et al., 2000), the establishment of EEZs did not put an end to fishing disputes (Jennings et al., 2009). Many countries had hoped that the new LOS would help resolving conflicts for natural resources (Balton, 1996). But once again, fish wars between coastal countries and distant waters fleets broke out (Joyner and von Gustedt, 1996). If UNCLOS had provided the legal framework for the management of fish resources within territorial waters, open access still applied in the high seas (beyond the 200 nautical mile limit). In 1982, only 10% of the world catches were taken beyond EEZs and the management of highly migratory species such as tuna had not been seen as a priority (Kaitala and Munro, 1993). Distant water fleets fishing on the high seas could do so under the regime of the "Freedom of the Seas". In principle, they should cooperate with coastal countries to manage straddling stocks (i.e. those spanning across EEZs and the high seas, Grzybowski et al., 1995; Joyner and von Gustedt, 1996). However UNCLOS provided no guidelines to meet these objectives of cooperation (Kaitala and Munro, 1993; Grzybowski et al., 1995), except that it could be achieved either directly, either through Regional Fisheries Management Organization (RMFOs).

From 1993 to 1995, the UN Conference on Straddling and Migratory Fish Stocks took place (Bjørndal et al., 2000). As the state of marine resources kept deteriorating, international conflicts between fishing States became more frequent. It became necessary to conclude an agreement to resolve the many conflicts that had arisen (Grzybowski et al., 1995). The 1995 United Nations Fish Agreement (UNFSA) provided rules for the management of straddling and highly migratory fish stocks that were missing in the convention of 1982. Since UNFSA, coastal and distant water countries have the duty to cooperate either directly or through RFMOs for the conservation, management and exploitation of straddling and highly migratory fish stocks. Countries have to cooperate to obtain the best scientific information and the precautionary approach applies. RFMOs can take different forms; some of them have a simple advisory role, while the others have the power to implement regulatory measures. Scientific information can be used to implement fishing quotas, effort or capacity limitations, or seasonal closures even when the level of uncertainty is high (Kedziora, 1997). Decisions are made on the basis of consensus between member States. In 2016, about 20 RFMOS almost entirely cover the world oceans (Cullis-Suzuki and Pauly, 2010). Four of them manage the highly migratory (i.e. travelling long distances) and straddling (i.e. spanning across EEZs and the high seas) tuna species (Figure 1.2).

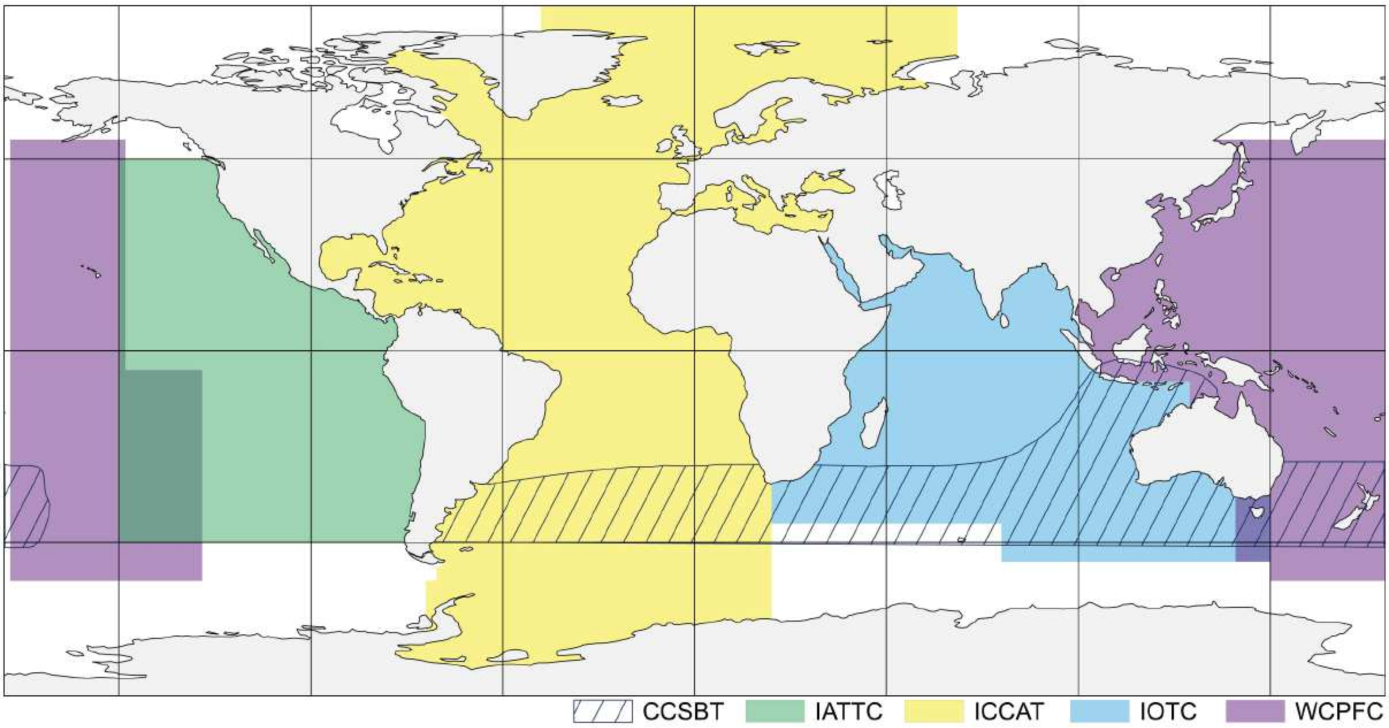


Figure 1.2: Regional Fisheries Management Organization (RFMOs) of the world oceans in 2016 (source: European Atlas of the Seas; http://ec.europa.eu/maritimeaffairs/atlas/index_en.htm)

Though RFMOs had existed since the 1950s, it was the first time they played such an important role in international fisheries management (Lodge et al., 2007). After UNFSA, many had hoped that this would be the solution to improve the management of migratory and straddling stocks. But RFMOs suffer from various problems (Lodge et al., 2007; Cullis-Suzuki and Pauly, 2010; Clark et al., 2015). First of all, the decision-making process generally requires finding a consensus between member States with very different economical, political, social or cultural objectives. Coastal states are generally developing countries with few resources to monitor and control their artisanal and semi-industrial fisheries. Distant water fleets generally originate from developed countries that have a strong geopolitical influence. Second, enforcement of the regulations applying in the high seas can be very difficult. Most RFMOs have made progress in these matters, with the introduction of vessel unique identifiers, logbooks (declarative catch data), observer programs and Vessel Monitoring System (VMS, a GPS system monitoring the position of fishing vessels). However, issues regarding the Illegal, Unreported and Unregulated fishing (IUU) remain important (Agnew et al., 2009) . Finally, the lack of appropriate regulations and the absence of efficient coercive tools have not solved issues of excess fishing effort and excess capacity. Distant water fleets generally benefit from direct subsidies to support investment or indirect subsidies through fishing agreements (OECD, 2006; Sumaila et al., 2010 ;Le Manach et al., 2013) which have been shown to encourage overinvestment in fisheries, leading to overcapacity. In the absence of agreed rules to regulate capacity, coastal countries may also be tempted by re-flagging foreign vessels (i.e. attribute their flag to a distant water vessel; Birnie, 1993) or by the attribution of many licences to foreign vessels through fishing agreements.

Though considerable effort has been deployed to improve the management of straddling and highly migratory stocks, there are still many challenges RFMOs have to address. In particular, how can we monitor and control changes in the modalities of use of fishing gears and technologies by distant water fleets? How can we reconcile the objectives of the many stakeholders of fisheries to make the necessary management decisions? Through the example of tropical tuna purse seine fleets operating in areas managed by the International Commission for the Conservation of Atlantic Tunas (ICCAT) and the Indian Ocean Tuna Commission (IOTC), the present thesis addresses some of these questions.

1.1.3 The development of the world tuna fisheries: a textbook case

Temperate and tropical tunas, that have long been an important resource for many coastal countries, are no exception to this recent history of world fisheries (Fonteneau, 1997). In about 60 years, their catches increased from less than 500 000 tons during the 1950s to 5.3 million tons in 2014. This represented about 8.8% of the total 79.7 million tons of world catches in 2012 (FAO, 2014). Because they represent such a vital resource to the many fishing nations that exploit them, tunas are the perfect case study to address the questions of fishing effort, fishing capacity and management of modern high seas fisheries. Local fishers have long exploited tuna for subsistence. For centuries, due to the limitations of their fishing vessels and to the migratory nature of many tuna species, they only caught tunas close to the coast. Fishers took advantage of particular seasonal migrations or particular stages of the life history of the tunas they exploited (Ravier and Fromentin, 2001). Then as now, multi-faceted fisheries targeted numerous tuna species using multiple fishing gears across the world (Miyake et al., 2004). Just like in other fisheries, the 20th century was the century of deep changes and growing concerns regarding excess fishing capacity, excess fishing effort and impacts on the functioning or marine ecosystems.

During the 1940s and the 1950s, the demand for canned tuna increased (Miyake et al., 2004; Gillet, 2007). Though local artisanal fisheries had long existed, industrial tuna fisheries rapidly developed and expanded at sea. During the 1950s, major tuna fisheries comprised of Japanese and US longliners (LL) and baitboats (BB) targeting yellowfin (YFT, *Thunnus albacares*) and albacore (ALB, *Thunnus alalunga*) tuna in the Pacific Ocean. Thirty years later, LL fishing had extended to the Atlantic and the Indian Ocean. Japanese longliners had developed extremely cold storage and deep longline gears (Miyake et al., 2004). As a consequence, all longliners had changed their target species and began to exploit bluefin (*Thunnus macoyii*, *Thunnus thynnus*, *Thunnus orientalis*) and bigeye tuna (BET, *Thunnus obesus*). The importance of BB fishing had been considerably reduced and fleets of purse seiners (PS) had developed, becoming the most important tuna fishing fleets. During the 1960s, US baitboats were almost completely replaced with purse seiners fishing tropical tunas associated with dolphins. Spanish and French purse seiners became more and more important from the 1960s to the 1970s in the Western Atlantic Ocean. The same Spanish and French purse seine fleets contributed to the development of a major purse seine fishery in the Indian Ocean during the 1980s. At the same time in the Pacific Ocean, purse seiners continuously extended their fishing grounds from the 1950s. This development was supported by the increasing contribution of floating objects in their catches of yellowfin, skipjack (SKJ, *Katsuwonus pelamis*) and bigeye tuna (Scott et al., 1992; Fonteneau et al., 2000).

After 60 years of expansion, the size of most fishing fleets has increased (Miyake et al., 2004). A wide variety of fishing gears and fishing nations target temperate and tropical tunas in all oceans from 50°N to 50°S (Fonteneau, 1997). Seven species of tunas are of major commercial importance and three species dominate world catches: skipjack tuna (2.9 million t in 2012), yellowfin tuna (1.4 million t) and bigeye tuna (0.4 million t). The Pacific Ocean is the main contributor to these catches, followed by the Indian and the Atlantic oceans (FAO, 2014). Four tropical tuna RFMOs are in charge of their management: the IATTC (iattc.org) created in 1949, the ICCAT (iccat.int) created in 1969, the IOTC (iotc.org) created in 1996 and the WCPFC (wcpfc.int) created in 2004. However, neither the creation of tuna RFMOs nor their adoption of regulatory measures has been sufficient to address the issues that tuna fisheries are facing (Cullis-Suzuki and Pauly, 2010).

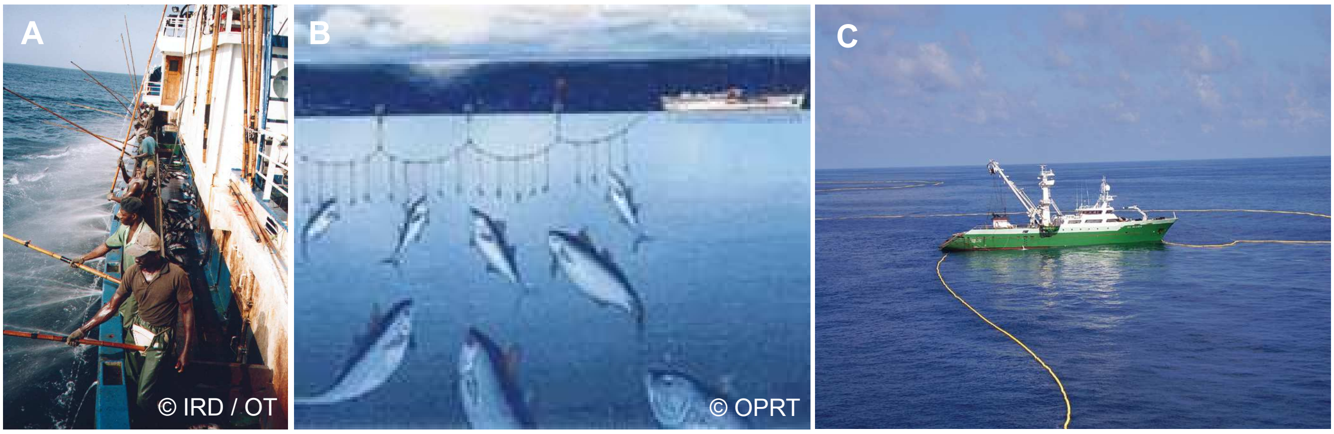


Figure 1.3: Main techniques used to fish tunas. A: baitboat. B: longline. C: purse seine.

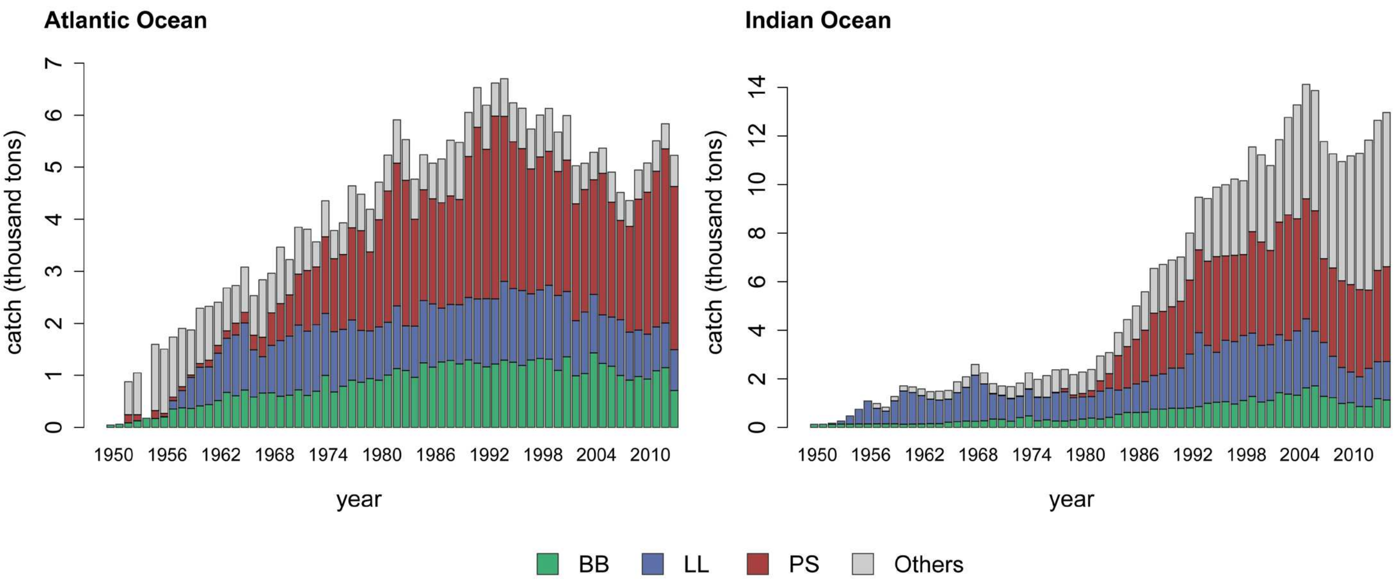


Figure 1.4: Evolution of catches per fishing gear in the Atlantic Ocean and in the Indian Ocean

First, about 40% of tuna stocks are overfished (ISSF 2016). The overexploitation of Atlantic bluefin tuna during the 2000s (Fromentin, 2010) has left an everlasting mark on the perceptions of tuna fisheries by the public, though bluefin tuna only accounts for 1% of the global catch. However, the situation is not always better for the important yellowfin and bigeye tropical tunas. Second, tuna fisheries suffer from a global problem of overcapacity (Joseph, 2003). This situation is encouraged by the multiplicity of fishing nations that are involved in the exploitation of tropical tunas, the use of flags of convenience by distant water fishing vessels

(Miyake et al., 2004), the development of fishing agreements since the creation of EEZs (Le Manach et al., 2013), and the allocation of subsidies to fishing fleets (Sumaila et al., 2010). Finally, tuna fishing also has negative ecosystem impacts, with sometimes high levels of bycatch of juveniles of tuna, sharks, sea turtles and marine mammals (Amandè et al., 2010; Hall and Roman, 2013).

The purse seine fishery in particular is criticised about the numerous Fish Aggregating Devices (FADs) used to catch tropical tunas (Fonteneau and Chassot, 2014), with an increasing pressure of environmental NGOs (Baske et al., 2012; Greenpeace France, 2014). However, some important questions for the management of this fishery remain unanswered. How many of these Floating Objects (FOBs) are currently in use? What are the strategies of fishers with FOBs? How do they affect their efficiency and their fishing strategies? Is the current management sufficient? If not, which management options would be appropriate? The present thesis aims to address these questions.

1.2. 1960s to 1990s: development of FOB fisheries

1.2.1. Associative behaviour of tropical tunas with FOBs

Fishers have long known that the objects drifting at the surface of the ocean (hereafter referred to as drifting Floating OBjects, 'FOBs') can attract various species of fish. For centuries, they have known that fish associated with FOBs are easier to detect and easier to catch. They have used this knowledge as an indicator of higher abundance, better catchability and increased fish school size (Fréon & Dagorn 2000; Dempster & Taquet 2004; Dagorn, et al. 2012). For a long time, they have relied on marine natural objects such as marine mammals or terrestrial wooden debris entering the ocean through river mouths ('natural logs', Figure 1.5 A-C). As the human population grew, river mouths began to bring debris of terrestrial activities and increasing amounts of fishing gears were lost or abandoned at sea (Caddy and Majkowski, 1996; Figure 1.5 D-E). By the 2000s, these 'artificial logs' had become a major component of the FOB population (Fréon and Dagorn, 2000). In addition to this opportunistic use of logs, fishers also began to build and deploy their own FOBs. These FADs were built and deployed to mimic the natural behavior of fish with logs (Figure 1.5 G-I). Such FADs have been used since ancient times to catch dolphinfish in the Mediterranean sea (Dempster and Taquet, 2004). However, the history of dFAD fisheries is a relatively recent one, with about a century of existence (Bromhead et al., 2003).

Nowadays, dFAD fisheries generally use bamboo, metallic of plastic rafts of 4 to 6 m2. These rafts are covered by old purse seine fishnets to make them as invisible as possible to prevent the dFAD from being stolen or used by other fishing vessels. Pieces of old fishnets that can reach depths of 15 to 100 meters are used as "anchors" in oceanic currents and to facilitate fish aggregation (Dagorn et al., 2013). Over time, various designs of dFADs have been used . There is no obvious difference between logs and dFADs in their ability to aggregate fish such as tropical tunas, nor between the different types of FOBs (Ariz et al., 1999). Nevertheless, the design of dFADs can improve their invisibility to other fishing vessels, prevent the losses of dFADs due to strong currents or reduce some negative impacts of the materials that are used (Dagorn et al., 2013). For example, dFADs of the Atlantic Ocean tend to have deeper underwater structures to slow down their drift and "eco-FADs" have been developed reduce the risk of entanglement of sharks and sea turtles in the old pieces of netting hanging under dFADs (Franco et al., 2012). In recent years, fishermen have developed «stealthy» dFADs which are generally built of metal pipes and designed so that the structure is located a few meters under the water to make it more difficult to detect.

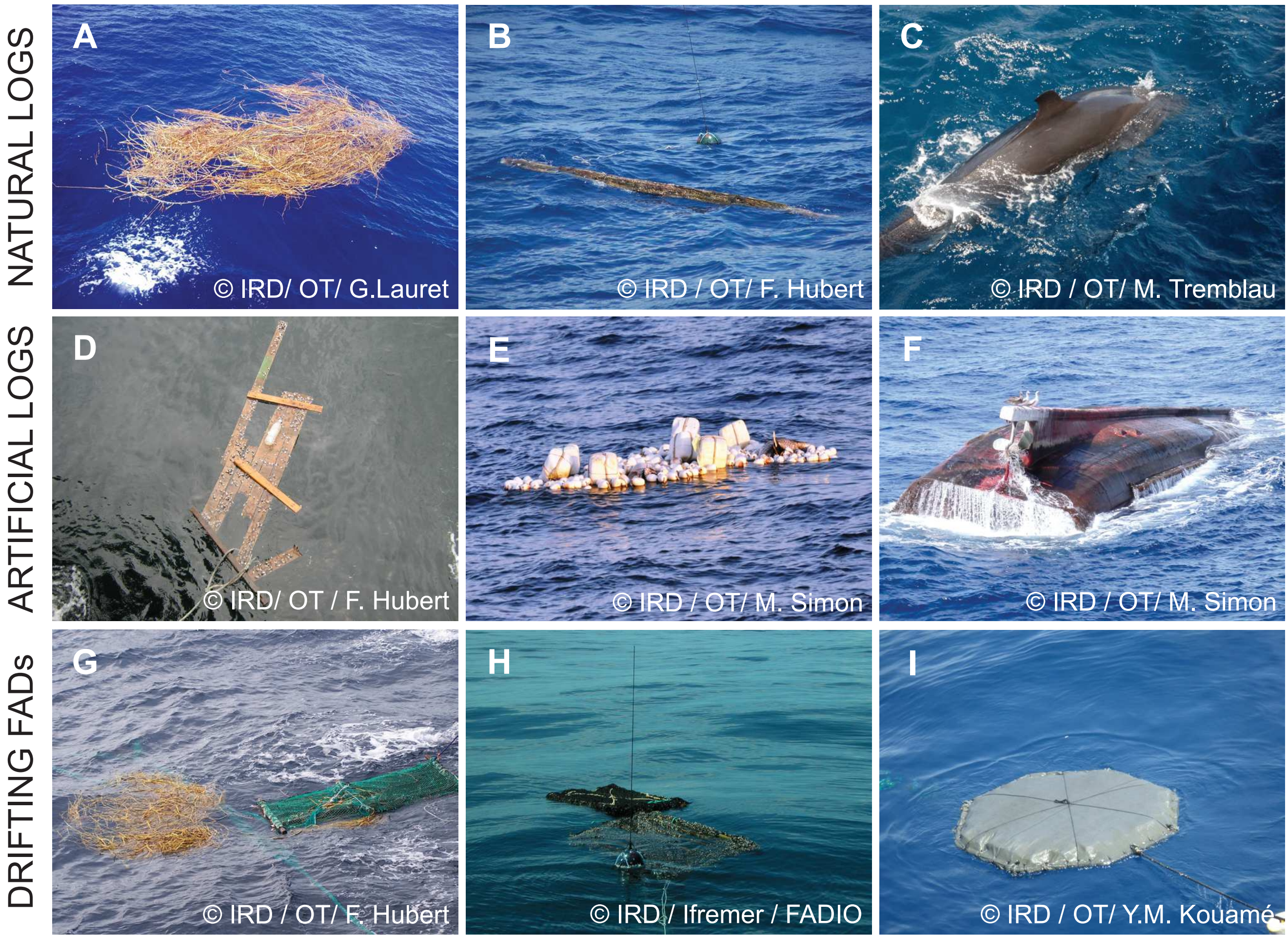


Figure 1.5: Typology of drifting Floating Objects (FOBs) used by tropical tuna purse seiners. A: "tas de paille" – B: wooden log – C: marine mammal – D: debris of terrestrial activities – E: wreck – G: natural log enhanced with a dFAD – H and I: different dFAD types (bamboo or plastic raft)

The reasons for fish associative behaviour with FOBs remain poorly understood. However, different hypotheses have been put forward, two of which have received considerable support. First, FOBs could act as indicators of zones of higher productivity and higher forage-fish availability (Hall, 1992). Logs from terrestrial sources originate in coastal or river waters that are likely to carry high concentrations of nutrients capable of generating significant levels of productivity. Terrestrial and marine logs can also concentrate in frontal or convergence zones known to have higher productivity levels (Olson et al., 1994). Secondly, FOBs could be meeting points for a given species and improve the encounter rate of isolated individuals or small size schools (Dagorn and Fréon, 1999; Fréon and Dagorn, 2000). In this hypothesis, FOBs would be used to reach the school "optimal size", as they can be detected further away than other congeners. Aggregating with a FOB could present the same evolutionary advantages as those that motivate forming schools; i.e. reducing the exposure to predation (especially for juvenile tunas) and enhancing the probability of finding food and breeding (Castro et al., 2002; Fréon and Dagorn, 2000).

Numerous tropical tuna and tuna-like species are attracted to FOBs, such as the commercially important skipjack, yellowfin and bigeye tuna. These three tunas are highly migratory pelagic species and therefore exploited by the large variety of fishing gears described previously, either under FOBs or in Free Swimming

Schools (FSC, i.e. unassociated). They generally aggregate with FOBs in multispecies schools comprised of various tuna, tuna-like, and bony fish species often associated with sharks, rays and sea turtles (Amandè et al. 2010). Schools are more closely associated with FOBs during the day than during the night (Schaefer and Fuller, 2013). Tunas caught on FOBs are generally smaller than those caught in FSC, with an average size of 50 cm FL, corresponding to adults of skipjack and juveniles of yellowfin and bigeye tunas (Fonteneau et al., 2000). The small, relatively fast growing, and fecund skipjack tuna dominate these catches destined for canning. Compared to skipjack tuna, yellowfin tuna (sold as fresh fish or canned) and bigeye tuna (principally caught for the sashimi market by longliners) have a relatively higher length at maturity and lower growth rate. Due to these important differences in their life history traits, yellowfin and bigeye tuna are more sensitive to overexploitation (Juan-Jordá et al., 2015).

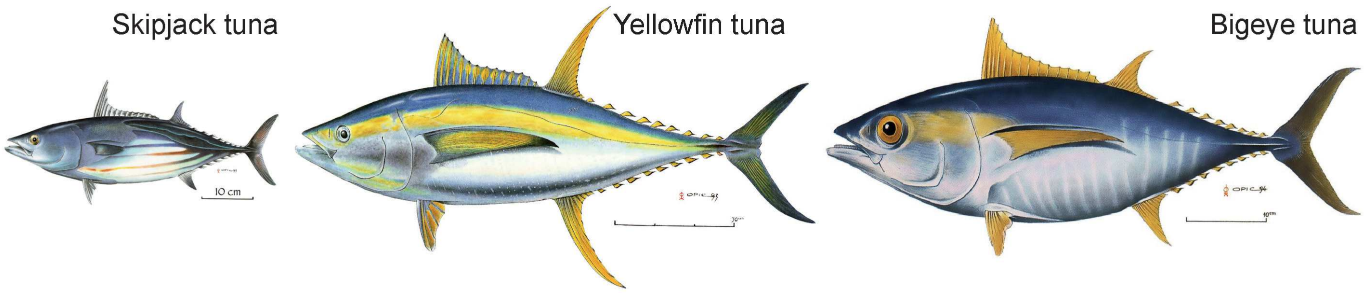


Figure 1.6: Main tropical tuna market species (copyright P. Opic)

1.2.2. From anchored to drifting FADs

In the early 1960s, the first French and Spanish purse seiners began to operate in the Atlantic Ocean (Postel, 1965). The first decades of the fishery were those of expansion. Within a few years, the minor purse fishery became the most important in terms of catches (Ariz et al., 1999). Until 1975 and the improvement of onboard conservation of catches, fishing activities remained in the coastal area where purse seiners mainly targeted yellowfin tuna free schools and to a lesser extent skipjack and bigeye tuna (Champagnat and Le Marrec, 1972; Ariz et al., 1999; Figure 1.7) In the Western Pacific Ocean and in the Indian Ocean, traditional fisheries had long used natural logs to catch tropical tunas (Fonteneau et al., 2000). In the Eastern Pacific Ocean, the baitboat fishery had been replaced by purse seiners targeting tropical tunas associated with dolphins in the late 1950s (Lennert-Cody and Hall, 2000; Miyake et al., 2004). Yet, at that time in the Atlantic Ocean, fishing sets on logs remained of little importance for purse seiners (Fonteneau et al., 2000) though fishers already showed an interest for fish behaviour with floating objects (Ariz et al., 1999; Stretta and Slepoukha, 1986). At the same time in the Indian Ocean, there was still no distant water fleet of purse seiners.

In the late 1970s and early 1980s, the situation of the Atlantic yellowfin stock, intensively exploited, led French fishing companies to the Indian Ocean (Hallier, 1988). From 1980 to 1983, several exploratory fishing campaigns took place in this ocean (Hallier, 1988; Marsac and Stéquert, 1983, 1984). Asian fleets of longliners had successfully developed in the Indian Ocean but surface fishing gears such as purse seine seemed inappropriate for this ocean due to a deep thermocline. But initial doubts were soon forgotten. There, logs were more abundant and could be used to stabilize fish schools and render them available closer to the surface (Marsac et al., 2014). In 1984, as yellowfin catch collapsed in the Atlantic Ocean due to a deeper thermocline event, the major part of the French and Spanish fleets left the Atlantic for the Indian Ocean (Ariz et al., 1999; Hallier, 1988; Marsac et al., 2014).

At the same time in the Pacific Ocean, since the late 1960s, anchored man-made floating objects (anchored Fish Aggregating Devices, aFADs) had been used in the Philippines as an efficient tool for baitboat and later for purse seine fishing. The success of this method encouraged pelagic purse seine fleets to deploy their own dFADs (Bromhead et al., 2000), with the support of fisheries scientists. In the early 1980s, Japanese scientists conducted experimental surveys in the Indian Ocean and concluded that there were not enough logs in this ocean to support a large purse seine fleet. Deployment of dFADs was proposed and studied as a solution (Marsac et al., 2000). In the Atlantic and Indian Oceans, European scientific experts also recommended dFADs as a viable solution to reach the full exploitation of stocks – notably the skipjack - and the profitability of the fishery. dFADs were then described as a mean to capture fast tuna schools (Bard et al., 1985; Stretta and Slepoukha, 1986) and the “cryptic” fraction of skipjack stocks (Ariz et al., 1999) that were less accessible to purse seine fishing. At a time when the objective of fisheries science was to support the expansion of the world fisheries, dFADs seemed to be a promising tool to develop purse seine fisheries.

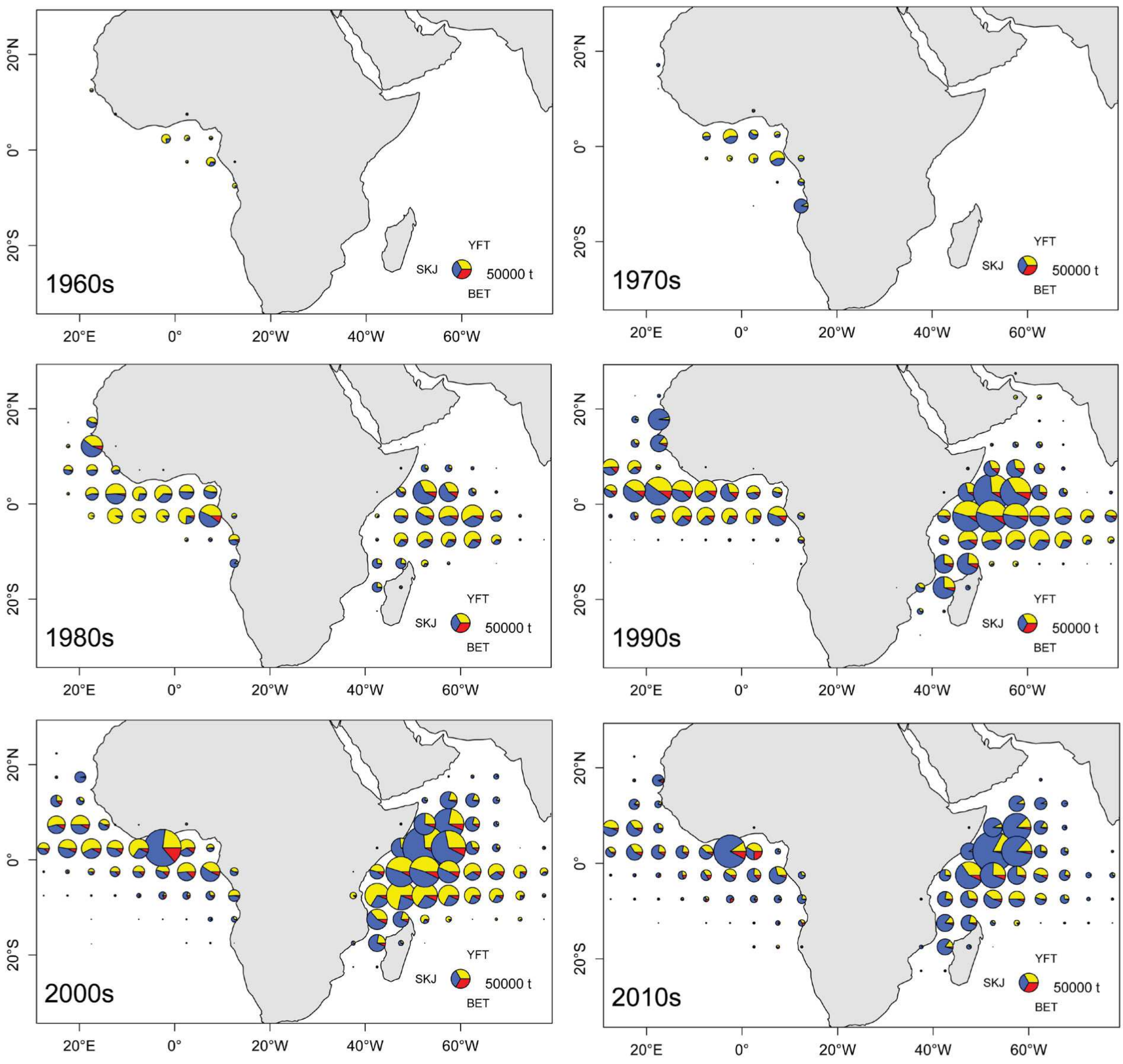


Figure 1.7: catches of tropical tuna skipjack (SKJ), yellowfin (YFT) and bigeye (BET) by tropical tuna purse seiners from the 1960s to the 2010s

1.2.3. Improvement of FOB fishing: tracking devices and support vessels

During the late 1980s and the early 1990s, the intensive dFAD fishery accelerated. Fishers of the Atlantic Ocean, at first reluctant to fishing on logs and dFADs, soon followed fishers from the Pacific and the Indian oceans where fishing on logs was more common (Hallier, 1995). This acceleration was supported by the gradual improvement of onboard technology both for FOB and FSC fishing. Among others, bird radars used to detect flocks of birds associated with tuna schools became more and more efficient, the size of purse seines and purse seiners increased and sonars were introduced to locate schools of fish in the water column (Gaertner and Pallares, 2002; Itano, 2002; Torres-Irineo et al., 2014). The size of purse seiners, that had long been restricted for questions of profitability increased. As fishing on FOBs developed and fishing technologies improved, larger amounts of tuna were caught and building larger vessels became profitable. The average size of purse seiners increased from about 42 m length overall for purse seiners built during the 1960s to more than 90 m in the 2000s (Figure 1.8). Some Spanish fishing companies rapidly specialized in a strategy of high productivity, by building very large purse seiners (>100 m), using support vessels and adopting targeting tuna associated with FOBs.

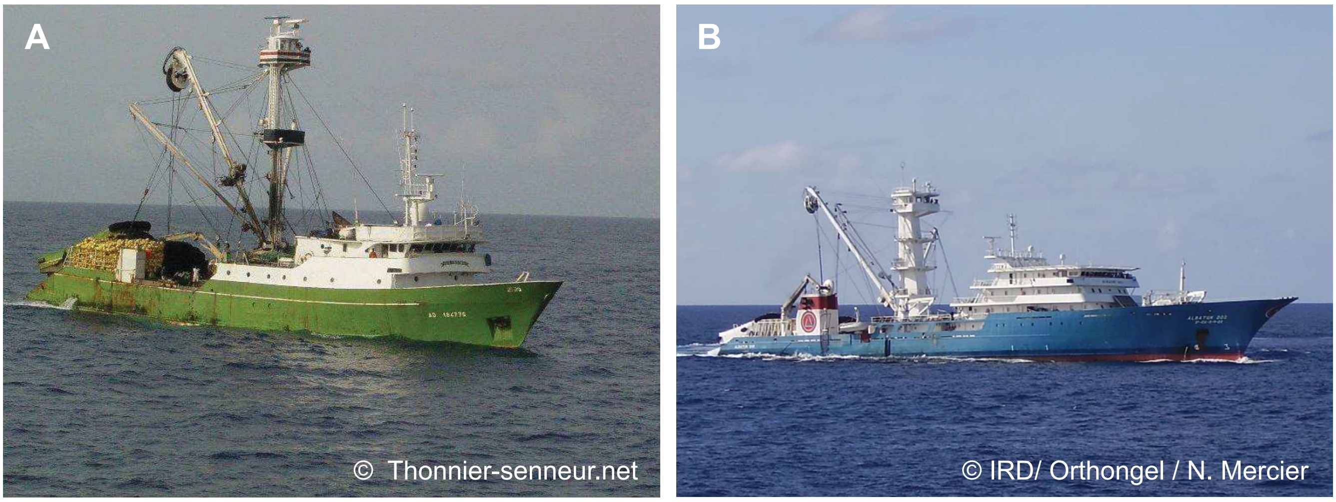


Figure 1.8: A:French purse seiner "Ile Tristan" built in 1975 (54 m). B: Spanish purse seiner "Albatun Dos" built in 2004 (116 m).

Specific technologies developed to track logs and dFADs while they drift. Radio beacons in the late 1980s and GPS buoys a decade later (Castro et al., 2002; Fonteneau et al., 2013) were used to monitor and facilitate the search of dFADs deployed at sea (Figure 1.9). Over time, their distance of emission and their battery autonomy improved, allowing monitoring increasing numbers of FOBs at the same time. The first tracking devices were HF radio buoys with a relatively small range of detection (generally less than 75 nautical miles, Itano et al., 2004). They could be easily detected and stolen by other vessels due to their long antennas (Ariz et al., 1999). They were progressively replaced with HF-GPS buoys and later by GPS buoys that transmitted their positions in real time. HF-GPS and GPS buoys contributed to the extension of fishing grounds in the Indian Ocean, as fishers had the possibility to monitor FOBs outside their traditional fishing grounds (Itano et al., 2004; Morón et al., 2001). For the first time, fishers could monitor an array of tracked FOBs on computer screens at all times. At the beginning of the 2000s, solar panels ensured a virtually limitless duration of emission of the GPS signal (Itano et al., 2004). A few years later, GPS-echosounder buoys were introduced by the Spanish purse seine fleet. In addition to the GPS signal, they provide information of the amount of biomass aggregated under FOBs. They further contributed to the efficient detection of associated tuna schools since the 2010s. Depending on the efficiency of the echosounder buoy, purse seiners can now avoid visiting FOBs that have not aggregated sufficient levels of biomass to undertake a fishing set (Lopez et al., 2014).

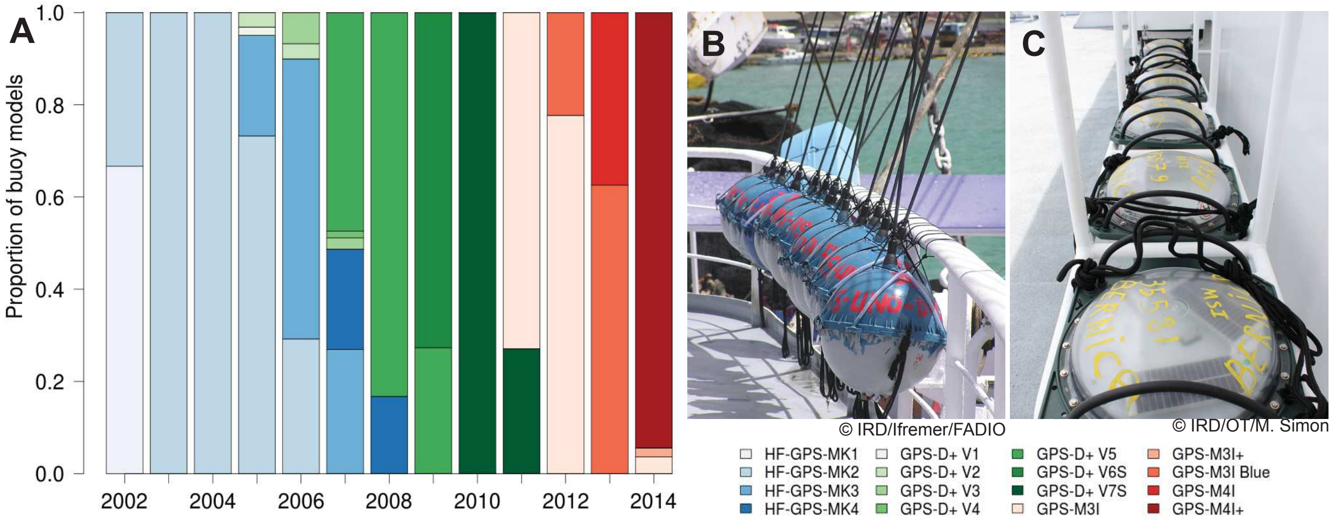


Figure 1.9: evolution of FOB tracking devices. A: relative proportions of radio and GPS buoys used by the French purse seine fleet in the Indian Ocean (2002-2014). B: example of simple GPS buoy (D+ Ariane). C: example of GPS – echounder buoy (M3i)

Figure 1.10: examples of support vessels. A: the French "Zéphyr" in the Atlantic Ocean. B: the "Ocean Scout" in the Indian Ocean.

At the same time, support vessels, in charge of assisting purse seiners in maintaining purse seiners' FOB array and detecting associated schools, were introduced (Arrizabalaga et al., 2001; Fonteneau et al., 2000, Figure 1.10). These vessels do not carry on any fishing activity. Instead, they collaborate with one or several purse seiners of the same fishing company to assist in the preparation of their FOB fishing activities. They can build dFADs, deploy new dFADs or transfer GPS buoys on FOBs already drifting at sea (i.e. replace a foreign GPS buoy by one of the purse seiners they assist). They also contribute to searching activities by visiting FOBs owned by the purse seiners they assist or searching for foreign FOBs, and providing information on FSC. When they detect aggregated tuna, they signal the position of the FOB and make sure that other vessels do not "steal" the fish they have detected by staying close to the object (Arrizabalaga et al., 2001). In the Indian Ocean, two of these support vessels even appropriated the seamount "Coco de mer" for several years (Ramos et al., 2010). Purse seiners benefiting from a support vessel can therefore focus on their searching and fishing activities, while support vessels are deploying dFADs and GPS buoys for them. Though support vessels are forbidden in the Eastern Pacific Ocean (IATTC resolution C-99-07), this is not the case in the Atlantic and the Indian Ocean where they are mainly used by the Spanish and Seychelles purse seine fleets (Morón et al., 2001; Ramos et al., 2010; Assan et al., 2015).

1.2.4. FOB fisheries of the Atlantic and Indian Oceans at the end of the 1990s

With all these changes, almost three decades after the start of the purse seine fishery, GPS buoy-equipped logs and dFADs had become an important mean of catching tropical tuna in the Atlantic and Indian oceans. Since the 1960s, purse seiners had gradually extended their fishing grounds, first in the Atlantic Ocean and then in the Indian Ocean (Figure 1.10). After 30 years of expansion, purse seiners were combining two different métiers, either targeting yellowfin tuna in FSC or skipjack tuna under FOBs. The purse seine fleet, that had long been a minor one, had become the most important in terms of catches in all oceans (Figure 1.3) with an increasing contribution of FOBs in to their catches. As the use of dFADs intensified, interest for dFADs, concerns for tuna stocks, bycatch species and pelagic ecosystems increased within the scientific community (e.g. Hallier et al., 1992; Ariz Telleria et al., 1999; Fonteneau et al., 2000). FADs had been recommended as the solution to reach the full exploitation of tropical tuna stocks. But there were soon growing concerns for the sustainability of this fishing practice.

1.3. 1990s to recent years: from profitability to sustainability concerns

1.3.1. Concerns for tropical tunas and other species

During the 1990s, questions of overexploitation, modification of the natural behaviour of tropical tunas and high levels of bycatch arose. As FOB fisheries were developing dramatically, scientists began to nuance the potential benefits of the use of FOBs in the light of these limitations (Ariz et al., 1999). Before the massive introduction of FADs, tropical tunas were principally targeted at bigger sizes in FSC. With the increasing contribution of FOBs, the patterns of exploitation of tropical tuna species have been strongly modified with a major decrease in the mean weight of yellowfin and bigeye over time (Chassot et al., 2015). Because skipjack, yellowfin and bigeye tuna present important differences in their life history traits, they respond differently to increasing fishing pressure. Among the three species, skipjack is considered to be the least sensitive, with a high rate of fecundity and size at maturity of 40 cm, a size that is close to that of recruitment to the purse seine fishery (Grande et al., 2014). However, yellowfin and bigeye tuna are mainly caught as juveniles of 40 to 60 cm under FOBs (Fonteneau 2013), that is to say before they reach their size at maturity (about 80-100 cm, Sun et al., 2013; Zudaire et al., 2013). Because these small fish could have grown to a much larger size, this may induce a situation of reduced yield per recruit for the whole fishery through a technical interaction with longline fisheries that target high value adult bigeye tuna for the sashimi market (Fonteneau et al., 2013).

In addition to these concerns of overfishing, there were soon concerns for the modification of the natural behaviour of tunas with floating objects. The idea of an ecological trap due to dFADs emerged among purse seiner skippers. This concept was debated and tested in the scientific community (Marsac et al., 2000; Hallier and Gaertner, 2008): the fast increase of dFAD use may trap tuna in suboptimal zones, where their condition factors decrease (Ménard et al., 2000) and their natural feeding migrations may be altered (Marsac et al., 2000). Though there is still much debate on the existence of such an ecological trap (ISSF, 2014), it is also possible that a too important use of FOBs contributes to a reduction of the size of tuna schools. Model simulations showed that numerous small size schools might colonize different FOBs when the density of FOBs exceeds a certain threshold (Sempo et al., 2013).

Finally, the increasing use of dFADs does not only have effects on tropical tunas. Compared to FSC fishing, FOBs can induce high levels of mortality for non-target species and vulnerable megafauna. In the Pacific Ocean, purse seiners have targeted tunas associated with dolphins since the 1950s. This method resulted in high mortalities of dolphins and caused considerable controversy during the 1960s and the 1970s. Purse seiners therefore turned to dFAD fishing which in turn resulted in increased levels of overall bycatch (Hall, 1998). The problem of bycatch was not a new one but there was an increasing awareness of the magnitude of the problem (Hall et al., 2000). In this context, the first estimations of bycatch levels were conducted for purse seine fisheries (Bratten and Hall, 1996; Stretta et al., 1998; Gaertner et al., 2002). In the Atlantic and Indian Ocean, a significant part of bycatch corresponds to juveniles of yellowfin and bigeye tunas (Amandè et al., 2010). However, various species of bony fish, billfish, sharks, and sometimes turtles and marine mammals are incidentally caught by purse seiners (Amandè et al., 2010, 2012; Escalle et al., 2015). Sometimes, it is even not necessary to perform a fishing set to cause such mortalities. The inappropriate use of old pieces of netting has been shown to cause important ghost fishing of sea turtles and sharks (Anderson et al., 2009; Gilman, 2011; Filmalter et al., 2013).

1.3.2. The problem of FOBs and fishing effort

Since the beginning of the fishery in the Atlantic Ocean during the 1960s and in the Indian Ocean in the early 1980s, tropical tuna purse seiners have continuously improved their fishing efficiency through the modification of vessel characteristics, the frequent introduction of new fishing devices and the development of new fishing strategies (Gaertner and Pallares, 2002; Torres-Irineo et al., 2014). Since the 1990s, FOBs and associated FOB technologies have greatly contributed to these changes and enhanced the catchability of tropical tunas by purse seiners. First, because FOBs contribute to the detection of tuna schools (Dagorn et al., 2013). Indeed, GPS buoys are used to accurately monitor their position (Fonteneau et al., 2000), echosounder buoys to monitor the amount of biomass aggregated under the FOB (Dagorn et al., 2013; Lopez et al., 2014) and support vessels to assist purse seiners in building, deploying and monitoring dFADs (Morón et al., 2001). Secondly, because FOBs increase the availability of tropical tuna to purse seiners by concentrating schools and increasing the proportion of successful sets (Miyake et al., 2010; Fonteneau et al., 2013) .

Due the increasing use of GPS buoy-equipped FOBs, traditional measures of fishing effort such as days at sea or fishing time have therefore become inappropriate for purse seiners using a combination of activities on FSC or randomly encountered FOBs (random search) and GPS buoy monitored FOBs (“directed” search). This complicates the definition of indices of Catch Per Unit Effort (CPUE) to assess the stocks of skipjack, yellowfin and bigeye tuna in RFMOs. In the absence of an appropriate measure of fishing effort, tuna RFMOs mostly rely on indices based on longliners. In addition, crucial information on the use of FOBs, GPS buoys, support vessels and changes in the efficiency of purse seiners are rarely taken into account and sometimes even not required by tuna RFMOs. As estimating the capacity of tropical tuna fishing fleets is still difficult

(Joseph, 2003; Reid et al., 2005; Morón, 2007) and concerns of overfishing have grown, in particular for yellowfin tuna in the Indian Ocean (IOTC, 2015), this does not provide the basis for an appropriate management of tropical tuna fisheries.

1.3.3. FOB fisheries in the Atlantic and Indian Oceans in the 2010s

Though concerns for tunas, bycatch and pelagic ecosystems have grown since the 1990s, FOB fishing kept on developing during the 2000s and the 2010s. Fishing grounds stopped expanding (Figure 1.7) but catches of the three main species reached historical levels of more than 400,000 tons in the Indian Ocean in 2003 and almost 300,000 tons in the Atlantic Ocean in 2013. Distant water fleets, benefiting from fishing agreements with coastal countries and re-flagging, are the major contributors to these catches. In 2014, European purse seiners (either French, Spanish or under a flag of convenience) contributed to about 40% and >90% of purse seine catches of skipjack, yellowfin and bigeye tuna in the Atlantic and Indian oceans respectively. In the Atlantic Ocean, additional Asian fleets of purse seiners operate under the Ghanaian flag. They contributed to about 20% of the catches of the three main species in 2014. Over the two last decades, the relative proportion of FOBs in the activities of purse seiners has increased. In 2014, approximately 75% and 80% of catches of purse seiners were made on FOBs in the Atlantic and Indian oceans.

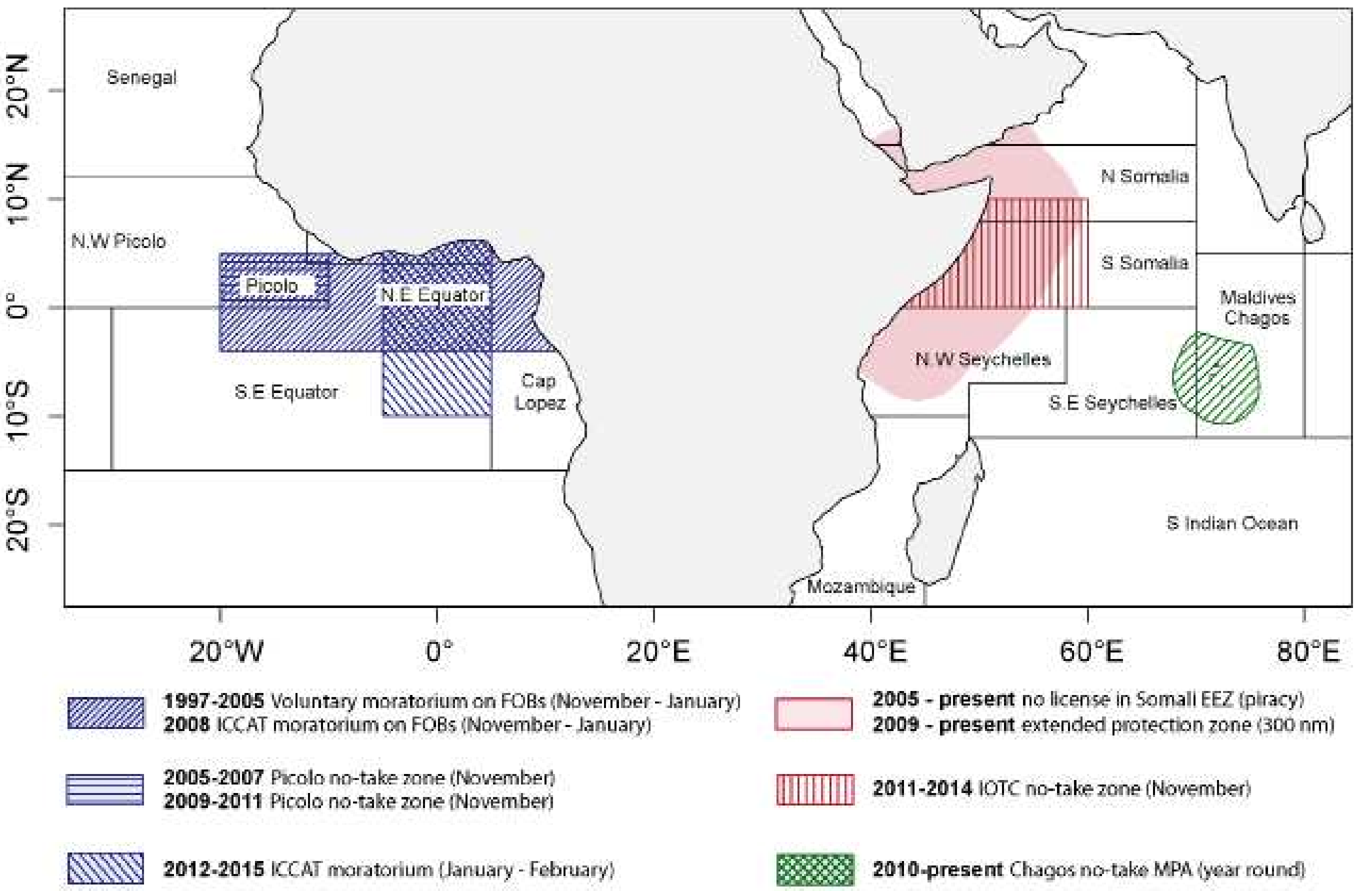


Figure 1.11: spatial management measures in the Atlantic and Indian Oceans

In 20 years, FOB fishing has strongly increased the effort of tuna fisheries in all oceans. FOBs have strongly contributed to the improvement of the efficiency of purse seine fishing (Le Gall, 2000;Gaertner and Pallares, 2002) and to the major increase in global tuna catch (Ariz et al., 1999; Fonteneau et al., 2013). However, they have also become a source of concern for the sustainability of the fishery, the state of tropical tuna stocks and the health of pelagic ecosystems (Dagorn et al., 2013; Fonteneau et al., 2013). In particular, though skipjack stocks are exploited at healthy levels, this is not the case of bigeye tuna in the Atlantic Ocean neither of yellowfin tuna in the Atlantic and Indian Oceans (ICCAT, 2015; IOTC, 2015). To date, management has primarily relied on various FOB moratoria in the Atlantic Ocean and time-area closures of purse seine fishing in the Indian Ocean (Torres-Irineo et al., 2011 ; Davies et al., 2012; Kaplan et al., 2014). These spatial management tools generally aimed at reducing catches of juveniles of yellowfin and bigeye tuna, but they often had a limited effect (Davies et al., 2014; Fonteneau and Chassot, 2014; Fonteneau et al., 2015). In the Atlantic Ocean, the frequent changes of size and location of FOB moratoria (Figure 1.11) is symptomatic of this absence of results, that were also due to non-compliance of non-European fleets (Torres-Irineo et al., 2011). In the Indian Ocean, a no-take area was put in place in 2011 but abandoned in 2015 (IOTC Res 12/03) for similar reasons of absence of efficacy. Purse seine fishing was prohibited in November but support vessels were allowed to visit the no-take zone (Martin et al., 2011). Other spatial regulations were adopted in recent years such as the implementation of a permanent no-take MPA covering the entire EEZ of the Chagos Archipelago (Koldewey et al., 2010; Sheppard, 2010). Finally, because of piracy threat and the absence of fishing agreements with Somalia, purse seiners did not have access to a large 300 nm zone off Somalia since 2009. Though not a proper management tool, this zone can be seen as an involuntary moratorium (Chassot et al., 2010). In addition since 2013, due to growing pressure of various environmental NGOs regarding the issues of bycatch and ghost fishing on FOBs, tuna RFMOs have started adopting FOB use regulations (Table 1.1).

Table 1.1: List of management measures relevant to FOB fishing by tropical tuna purse seiners in the Atlantic and Indian Oceans. Note that some measures are not directly related to FOBs but may have an impact on FOB fishing (e.g. catch quotas).

Category	Tools	Atlantic Ocean (ICCAT)	Indian Ocean (IOTC)
Management plans	dFAD management plans	Yes (Res 15-01)	Yes (Res 15-09)
Conservation measures	Capacity/effort limitation on FOBs	No	No
	Limitation of the number of GPS buoys	Since 2015 (Res 15-01)	Since 2015 (Res 15-08)
	dFAD moratorium	Yes (Gulf of Guinea)	No
	Discard ban	No	Yes (Res 15-06)
	Non-entangling dFADs	Yes	Yes (Res 13-08)
	Biodegradable dFADs	No (recommended)	No (recommended)
Data collection, reporting, control	FAD logbooks	Yes	Yes (Res 13-08)
	Reporting obligation on numbers of dFADs deployed	Yes (per year)	Res 13/08: dFAD logbooks Res 10/02: support vessels logbook
	Reporting obligation on dFAD fishing sets	Yes	Yes
	Reporting obligation on support vessels	Yes (data not available)	Yes (data not available)
	Onboard observers	100% since 2015	100% since 2015
Other regulations (not FOB specific)	Catch quotas	Yes (BET + YFT, Res 15-01)	No
	Record of vessels	Yes	Yes (Res 15-04)
	Capacity limitation / effort limitation (general)	Yes (Res 15-01)	Yes (Res 15-01)

In the Atlantic and the Indian Oceans, purse seine fleets have now an obligation to adopt “FAD management plans” (ICCAT Res 15-01 / IOTC Res 13-08). Purse seine fleets should report various information on their use of FOBs (types of FOBs, types of tracking devices, numbers per year or quarter, etc) and are responsible for managing their use. Nevertheless, these “FAD management plans” can take various forms depending on the fleet and are not real management measures. More recently, the IOTC adopted in 2015 a limitation 550 of active GPS buoys per vessel (at any time) complemented by a limitation of 1,100 GPS buoys purchased per year and per vessel (Res 15-08). This decision was soon followed by the ICCAT (Res 15-01) and applies for the first time in 2016. Other management tools, that are not necessarily FOB specific apply, such as catch quotas for BET and YFT in the Atlantic Ocean, a general limitation of fleet capacity in both oceans or a discard ban in the Indian Ocean. However, other issues of importance, such as the absence of catch quotas in the Indian Ocean, the absence of specific regulations of the use of support vessels, or explicit regulation of fishing effort on FOBs are not addressed by current management.

1.4. Objectives and structure of the thesis

Despite the importance of FOB fishing and growing pressure for dFAD management plans in tuna RFMOs, many questions regarding the modalities of dFAD and GPS buoy use are still difficult to answer. Where, when and how are these objects deployed in the Atlantic and Indian Oceans? How many of them are currently drifting at sea? What are the consequences for target species, non-target species and pelagic ecosystems? In particular, how do dFADs and GPS buoys contribute to increase the fishing effort and the efficiency of purse seiners? Are the existing management tools appropriate to address the specificity of FOB fisheries? If not, which management decisions should be made and how can we reconcile the objectives of the many stakeholders involved in FOB fisheries? As none of the implemented management plans has had the expected outcomes (Marsac et al., 2014) , answering these questions may be of primary importance to solve management issues. Over time, several elements of the response have been provided to fill in these knowledge gaps. Catch and bycatch data have been extensively analysed and differences in species composition between FOB and FSC as well as seasonal changes are well known (Amandè et al., 2011, 2012; Dagorn et al., 2013; Fonteneau et al., 2013). Much effort has also been dedicated on studying the behaviour of fish at FOBs and its consequences for fragile bycatch species (e.g. Filmalter et al., 2013) and tuna distribution (e.g. Capello et al., 2012; Sempo et al., 2013). Due to data availability, they mainly consider the FOB fishery from the point of view of fish and little recent information from fishers and fishing gears perspective is given. For example, the last descriptions of dFAD deployment seasons dates from the beginning of the 1990s in the Indian and Atlantic Oceans (Hallier et al., 1992, Ariz Telleria et al., 1999).

CHAPTER 1 presents a methodology to identify phases of drift in GPS-buoy equipped FOB trajectories. On the basis of discriminative classification methods, the successive positions of GPS buoys used to monitor FOBs (either logs or dFADs) by the French purse seine fleet are separated into two classes: on board or at sea. Here, using the first dataset available for the GPS buoys used by the three French fishing companies operating in the Atlantic and the Indian Oceans, we compare four discriminative classification methods (velocity filter, Multiple Logistic Regression, Artificial Neural Network and Random Forest) to separate on board and at sea FAD positions and identify drift phases along the FAD trajectories. We firstly combine the information available on the GPS buoys and the trajectories of fishing vessels derived from their Vessel Monitoring System (VMS) positions, to manually identify the class of a fraction of the GPS buoy positions and build a learning dataset. We propose a methodology for calibrating, assessing and correcting the performances of the classification models, based on the objective of correctly identifying FAD drifting phases and avoiding inappropriate segmentation of the trajectories. At sea positions are used to provide preliminary information on FOB use such as the time at sea, the proportion of FOBs drifting outside fishing grounds and the proportion of FOB beaching. Chapter 1 was published as:

Maufroy, A., Chassot, E., Joo, R., and Kaplan, D. M. 2015. Large-Scale Examination of Spatio-Temporal Patterns of Drifting Fish Aggregating Devices (dFADs) from Tropical Tuna Fisheries of the Indian and Atlantic Oceans. PLoS ONE, 10: e0128023.

In CHAPTER 2, the classified trajectories of GPS buoys used by the French purse seine fleet over 2007-2013 are combined with multiple sources of information: positions of French fishing sets on FOBs, data collected through French and Spanish on board observer's programs and interviews with purse seine skippers. In a first step, key factors determining the deployment of dFADs and GPS buoys are examined. Four different seasons of GPS buoy deployment are identified in the Atlantic and Indian Ocean. These seasons are compared to FOB fishing seasons of the French purse seine fleet and to seasonal patterns of currents. In a second step, GPS buoy and observer datasets are combined within a raising procedure to estimate the total number of GPS-buoy equipped dFADs and GPS-buoy equipped FOBs used by all purse seine fleets in the Atlantic and Indian Oceans over 2007-2013. Results indicate a fast increase in the use of dFADs and GPS buoys in recent years and a strong modification of the natural pelagic habitats in both oceans. Chapter 2 was published as as:

Maufroy, A., Kaplan, D. M., Bez, N., Delgado de Molina, A., Murua, H., and Chassot, E. 2017.
Massive increase in the use of Fish Aggregating Devices by purse seine fisheries in the Indian and Atlantic Oceans. ICES Journal of Marine Science, 74(1), 215-225).

CHAPTER 3 addresses the question of measuring the fishing efficiency of European Union (EU) tropical tuna purse seine fleets in relation to their increasing use of dFADs and GPS buoys. French and Spanish logbook data, characteristics of French and Spanish purse seiners as well as the links between purse seiners and their support vessels are first used to analyse temporal changes in the strategies of EU purse seiners with FSC and FOBs. Then, 5 different dimensions of the efficiency of tropical tuna purse seiners (catch per day, catch per set, catch per travelled distance, number of fishing sets, travelled distance) are analyzed with GLMMs. The contribution of the size of purse seiners, period of construction, use of support vessels and strategies with FOBs and FSC to these 5 dimensions is measured and used to derive indices of fishing power over 2003-2014 in the Atlantic and Indian Oceans.

Finally, in CHAPTER 4, interviews with purse seine skippers are used to understand their perceptions of the impacts of the FOB fishery and the potential for management. Interviews are conducted in two phases. First, 14 purse seine skippers were interviewed in the port of Victoria (Seychelles) from June to July 2013. These interviews were used as a complementary source of information to identify key questions for the evaluation and the management of the FOB fishery and to guide statistical analyses throughout the present thesis. In a second step, additional interviews were conducted with 15 skippers from August to September 2015.

Main results of the present thesis were presented to skippers to understand their perceptions of the impacts of the increasing use of dFADs in the Indian Ocean. Existing management and potential tools that could be used to manage tropical tuna purse seine fisheries were also discussed.

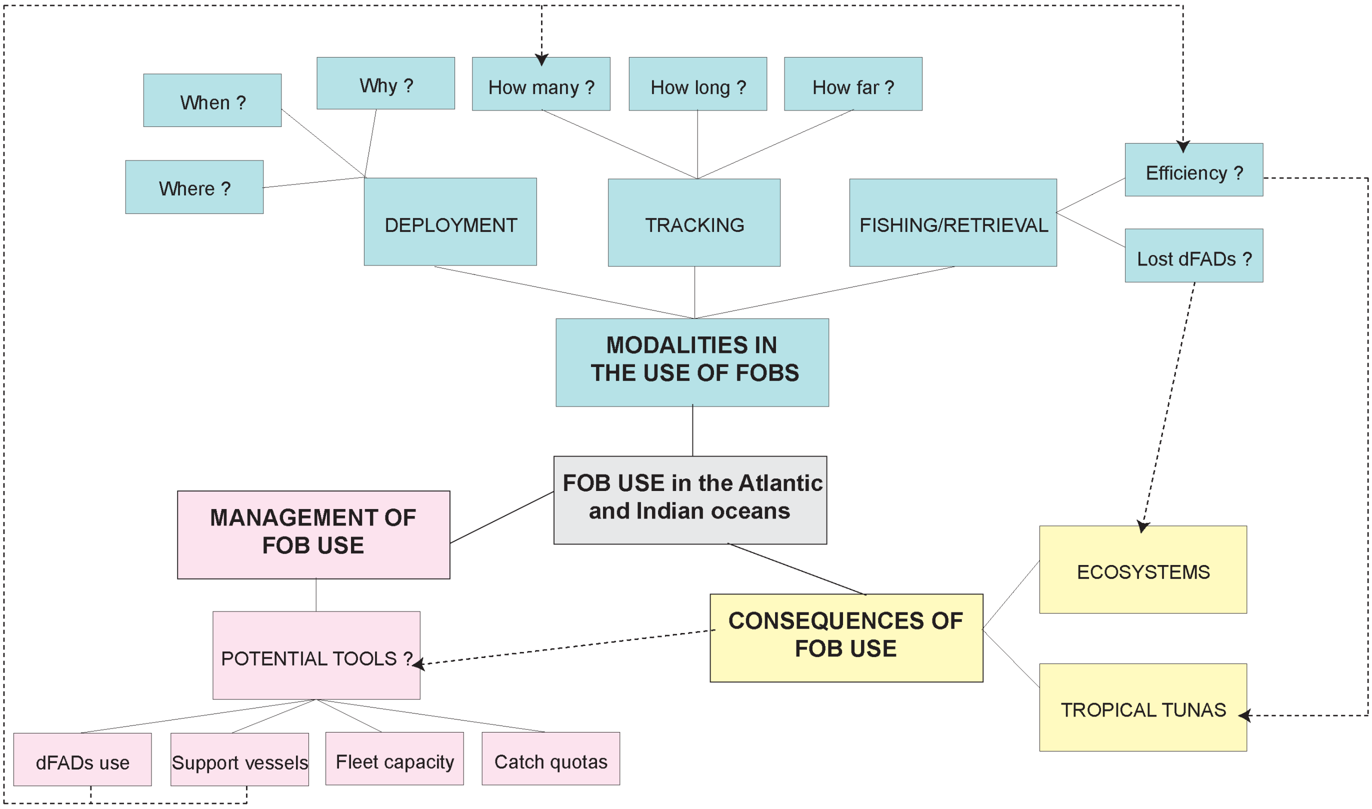


Figure 1.12: summary of the questions addressed by our research. Three main topics were addressed: the modalities in the use of FOBs, their consequences and the potential management of the fishery.

CHAPTER 1:

Large scale examination of spatio-temporal patterns of drifting Floating OBjects (FOBs) from tropical tuna fisheries of the Indian and Atlantic Oceans

2.1 Objectives of the chapter

Despite the serious concerns raised by the massive deployment of dFADs regarding their impacts on tuna and sensitive bycatch species (such as sharks and turtles) populations, and the possible changes in ecosystem functioning, very few information is available on the modalities of dFAD use. Such information is yet crucial for an effective assessment and management of tuna stocks within Regional Fisheries Management Organisations. In recent years, the ICCAT and the IOTC have improved the collection of such data, through the implementation of "FAD management" plans by tropical tuna purse seine fleets in the Atlantic and Indian Oceans (ICCAT Res 15-01, IOTC Res 15-09). Purse seine fleets report aggregated (per quarter or per year) but not detailed information on their use of dFADs and GPS buoy-equipped FOBs. This information sometimes correspond to a number of dFAD/GPS buoy deployments or to a number of active GPS buoy-tracked FOBs (Delgado de Molina et al., 2014; Goujon et al., 2015). Detailed positions on the use of GPS-buoy equipped FOBs could greatly improve the monitoring of the fishery, the assessment of its impacts and its management. However, such data, that reflect fine scale strategies of tropical tuna purse seiners, generally remain confidential.

For the first time, under an agreement with the French purse seine fleet, the 3 French fishing companies operating in the Atlantic and Indian oceans provided information on the positions of their GPS buoys. The data contains a succession of "on board" and "at sea" positions of GPS buoys that require a separation in order to be used. In this chapter, we present a methodology for separating phases of drift and transportation aboard purse seiners in GPS buoy trajectory data, by comparing the performances of four discriminative classification methods. Second, we derive from the reconstructed trajectories of GPS buoy-equipped FOBs the first estimations of dFAD time and distance at sea, illustrating some major differences in their dynamics and seasonality between the Atlantic and Indian oceans. Classified FOB trajectories are also used to provide the first description of spatial patterns of dFADs drifting at sea. Finally, we discuss the potential impacts of FOBs on sensitive habitats through an estimation of dFAD loss onshore and introduce the question of the measure of effective dFAD fishing effort.

In chapter 1, we have decided to keep the terminology used in the published version of our work (Maufroy et al., 2015). In this chapter, we do not make the distinction between FOBs deployed by tropical tuna purse seiners and FOBs naturally drifting in the Atlantic and Indian Oceans, as this information can only be found in observer data used in chapter 2. The term "dFAD" is therefore used for any type of FOB.

2.2 Introduction

It has been known for millennia that objects drifting at the surface of the ocean, hereafter referred to as drifting Fish Aggregating Devices (dFADs), attract various species of fish, though the reasons for this behaviour remain poorly understood (Fréon and Dagorn, 2000; Castro et al., 2002). Fishers have used dFADs for centuries as indicators of higher abundance, better catchability, increased fish school size and ultimately to facilitate the capture of fish (Fréon and Dagorn, 2000; Dempster and Taquet, 2004). Originally, dFADs were either natural marine objects, such as algae or marine mammals, or terrestrial wooden debris, e.g. entering the ocean through river mouths (Greenblatt, 1979). Since the late 1980s, however, the use of man-made dFADs by pelagic purse-seine fleets has become widespread. They generally consist of a bamboo raft covered with old pieces of purse seine netting and vertical filaments also made of netting hanging down beneath the raft serving as a subsurface drogue (up to 100 m) (Scott et al., 1992; Ariz Telleria et al., 1999; Fonteneau et al., 2000a; Bromhead et al., 2003). In tropical tuna fisheries, artificial dFADs have become increasingly important over time and annual global purse seine tuna catches on dFADs reached more than 1.5 million tons in the last decade (Dagorn et al., 2013; Fonteneau et al., 2013). The massive development of the dFAD-associated fishery has introduced major changes to the efficiency and selectivity of purse seiners that are not well reflected in traditional indices of fishing effort, such as time-at-sea or search-time. This has hindered the use of purse-seine catch rates for the estimation of tuna abundances needed for stock assessment (ISSF, 2012; Fonteneau et al., 2013). In addition, the extensive use of dFADs has raised serious concerns regarding increased bycatch and juvenile catch, reductions in tuna survival and fitness, and changes in ecosystem functioning (Marsac et al., 2000; Ménard et al., 2000; Hallier and Gaertner, 2008; Fonteneau et al., 2013). Despite these concerns, little information has previously been available on dFAD use worldwide. Such information is crucial to monitoring and management of the impacts of dFADs on pelagic ecosystems. As a result, Tuna Regional Fisheries Management Organisations (T-RFMOs) have recently called for dFAD management plans, including data collection on deployment and use of dFADs by purse seiners and supply vessels (e.g. Resolution 12/08 of the IOTC; IOTC, 2012).

Here, we present the first detailed, spatially-extensive treatment and analysis of the use of dFADs by purse-seiners in the Indian and Atlantic Oceans. We focus on the French component of the fishery, representing an annual catch of about 125,000 t, more than 20% of the total catch on dFADs in these oceans (Floch et al., 2012a, 2012b). French tuna purse seiners began to build and deploy artificial drifting bamboo rafts equipped with radio-range transmitters in the late 1980s (Morón et al., 2001). Detailed records of the positions of floating objects only became available with the emergence of GPS-equipped, satellite-linked buoys in the late 1990s which were coupled to a GIS software system onboard the vessels to monitor dFAD positions in near real-time. However, despite the intensification of dFAD fishing, information on buoy positions has remained highly confidential until recently. Under an agreement with the French purse seine fleet, we have obtained detailed dFAD tracking information for the period 2007-2011 from the 3 French purse seine fishing companies operating in the Atlantic and Indian Oceans.

Our objectives here are (1) to develop the baseline methodology for treatment and analysis of dFAD GPS positions and (2) to carry out an initial examination of dFAD spatio-temporal use and potential impacts. As dFADs data contain both positions while the dFAD was onboard the purse-seine vessel and positions while the dFAD was drifting at sea, four discriminative classification methods are compared for their ability to correctly identify dFAD drift phases on a subset of the data with known state. The classification method with the highest performance is then applied to the full dataset and used to describe the spatio-temporal patterns of dFAD use by a major component of the tropical tuna purse seine fishery in the Atlantic and Indian Oceans. Classified data serve as a basis (i) to identify dFAD density hotspots and measure time and distance at sea, all essential to understanding the impacts of an array of floating objects on tuna stocks and pelagic ecosystems, (ii) to detect dFAD beaching events and their corresponding deployment positions so as to evaluate potential damage to fragile coastal ecosystems and propose management strategies, and (iii) to identify “ineffective” or “ghost” dFAD fishing effort as characterized by dFADs moving out of established fishing areas.

2.2 Material and Methods

2.2.1 Fisheries data and FAD use overview

Data on catch and effort of French purse seiners have been collected by the 'Institut de Recherche pour le Développement' (IRD) since the development of the fishery in the Atlantic and Indian oceans in the early 1970s and 1980s, respectively. For the present study, fine-scale operational data based on skipper logbooks were available for the period 2007-2011. They describe the activities of purse seiners, the association type of tuna schools detected (i.e. free swimming or dFAD-associated school), the positions of purse seine fishing sets, as well as the tonnage and commercial size categories of tuna catches. Similar catch and effort data are available for other components of the purse-seine fishery, notably the Spanish fleet, on a 1º lon-lat grid. In addition, French purse seiners have been equipped with Vessel Monitoring Systems (VMS) since the early 2000s as part of the monitoring, control, and surveillance program of the European Union. The GPS position of each vessel is recorded on an hourly basis, enabling construction of vessel-specific trajectories over their typical 4-6 week fishing trips. This data can be used as a complement to buoy position data, in particular to help identify time periods when buoys were not in the ocean.

Before discussing dFAD position data, it is important to understand how dFADs are used by fishers. When leaving the port, purse seiners bring on board GPS buoys, bamboo rafts and/or the necessary material to build them. These will be used to maintain an array of dFADs belonging to the vessel. This can be done either by deploying new dFADs equipped with GPS buoys, equipping natural floating objects with GPS buoys or appropriating a floating object owned by another vessel by replacing its GPS buoy. Activities related to dFADs and buoys can also be conducted by auxiliary vessels that generally collaborate with 1-2 purse seiners (Ramos et al., 2010). GPS buoys are turned on before being deployed on a floating object to assure they are functioning correctly. During this period, which can last from a few hours to a few weeks, the GPS signal, transmitted via satellite through systems such as Inmarsat D+ or Iridium, is a sequence of "on board" positions that are similar to VMS positions of the fishing vessel. GPS buoys are then deployed on dFADs for a period of days to months during which time tuna may aggregate under the dFAD. When the level of aggregation is acceptable, a fishing set may be undertaken, either by the deploying vessel, or any vessel that has detected the tuna school. During the fishing set, the dFAD and/or GPS buoy may be retrieved or left at sea. GPS buoy tracks are therefore a succession of "on board" and "at sea" positions. Whereas GPS buoys belong to a single vessel, they may be moved from one floating object to another several times over their life-cycle, be retrieved and changed by foreign vessels operating in the same zone, and the objects they are attached to may be used by multiple vessels.

All these activities occur on fishing grounds that are common to European (mainly France and Spain) and Asian purse seine fleets, either in the open ocean or in Economic Exclusive Zones (EEZ) through fishing licenses. In the Indian Ocean, purse-seine fishing is highly seasonal with a primary peak of activity on floating objects during the third quarter of the year when the fleet concentrates off the coast of Somalia and a secondary peak from March to May when the fleets concentrates in the Mozambique Channel (Kaplan et al., 2014). In the Atlantic Ocean, the seasonality in dFAD activities is less important but a low season occurs from June to August (Ariz Telleria et al., 1999).

Once deployed, dFADs share many characteristics with typical Lagrangian drifters used in oceanographic studies, but differ in several important ways. First, the drogue beneath the dFAD is longer than what is typically used in oceanographic studies (up to 100 m). This generally slows the movement of dFADs with respect to surface currents, which is considered desirable by fishers for successful aggregation of tunas. Second, the technology of dFAD tracking buoys is somewhat different, including the use of electronic protection keys to prevent use of the buoys by non-owner vessels, solar panels to increase the buoy battery lifetime, and two-way satellite communications so that the frequency of emission of the GPS signal can be remotely controlled by the owning vessel (Fonteneau et al., 2000; Castro et al., 2002; Dagorn et al., 2013).

2.2.2 dFAD GPS buoy data and pre-processing

dFAD GPS buoy raw data provided by the 3 French fishing companies consist of GPS positions described by latitude and longitude, time of acquisition of the GPS signal (date and hour, with no information on the minute of acquisition of the signal), a vessel identifier and surface water temperature (°C). Timesteps between consecutive data points are irregular (i.e., 1 h, 6 h, 12 h, 1 d or more) depending on the intended use of the dFAD at a given time (e.g.when a fishing vessel intends to visit a given dFAD, it reduces the time between two emissions of a GPS buoy to 1 hour). Several vessels can monitor the same buoy during the same hour, resulting in repeated space-time positions. Furthermore, because time was only recorded to hours (i.e., minutes and seconds were not recorded) in the raw data, a similar time of emission can refer to several different positions during the same hour. We eliminated duplicate timesteps by calculating a unique position as the geographic midpoint of the different positions available for a given hour. Rare records without a valid latitude or longitude were eliminated. Buoys also occasionally erroneously produce two consecutive identical positions separated by a finite period of time. These "doubled" positions can produce inconsistent, extremely-high perceived speeds (reaching sometimes 100 m.s-1) between the second repeated position and the position immediately after it. We eliminated such repeated positions, keeping only the first of the two identical positions.

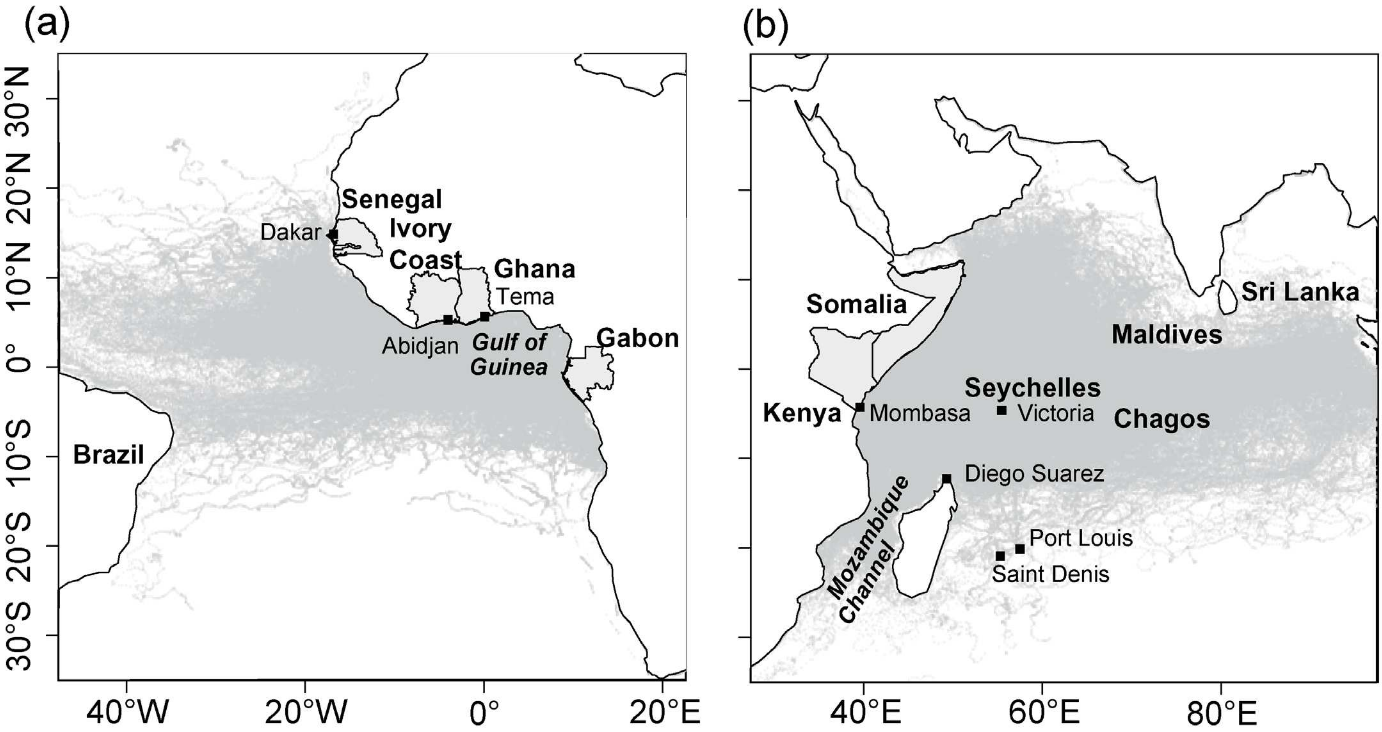


Figure 2.1: Location of raw GPS buoy positions in the Atlantic (a) and Indian (b) Oceans from January 2007 to December 2011.

Table 2.1: Yearly proportion of vessels of the French purse seine fishing fleet for which information on GPS buoys was available during 2007–2011 in the Atlantic Ocean (AO) and Indian Ocean (IO).

Year	AO	IO	Coverage (%)
2007	3/5	16/19	79.2%
2008	5/7	16/19	87.5%
2009	7/10	14/18	75%
2010	10/10	13/13	100%
2011	9/9	13/13	100%

The resulting dataset is stored in a PostGreSQL 9.1.9/PostGIS 2.0.1 database, and includes approximately 1,741,000 positions from 9,289 buoys used by 29 purse seiners operating in the Atlantic and Indian Oceans during the period 2007-2011 (Figure 2.1). The fraction of purse seiners and auxiliary vessels that have provided GPS buoy positions varies between years and fishing companies, with a gradual increase towards 100% coverage of French fishing vessels in recent years (Table 2.1). Given the complex utilisation of dFADs and GPS buoys described in the previous section, it is useful to define specific terminology for different parts of the dFADs positions dataset. Position data are referred to as "GPS buoy positions". The term "GPS buoy track" is used to refer to the ensemble of positions belonging to a single GPS buoy. Tracks are broken down into "on board" and "at sea" trajectories, consisting of sequences of positions classified as having a consistent state. "At sea" trajectories are also referred to as "dFAD trajectories" or "dFAD positions" as these correspond to periods the GPS buoy is generally attached to a dFAD.

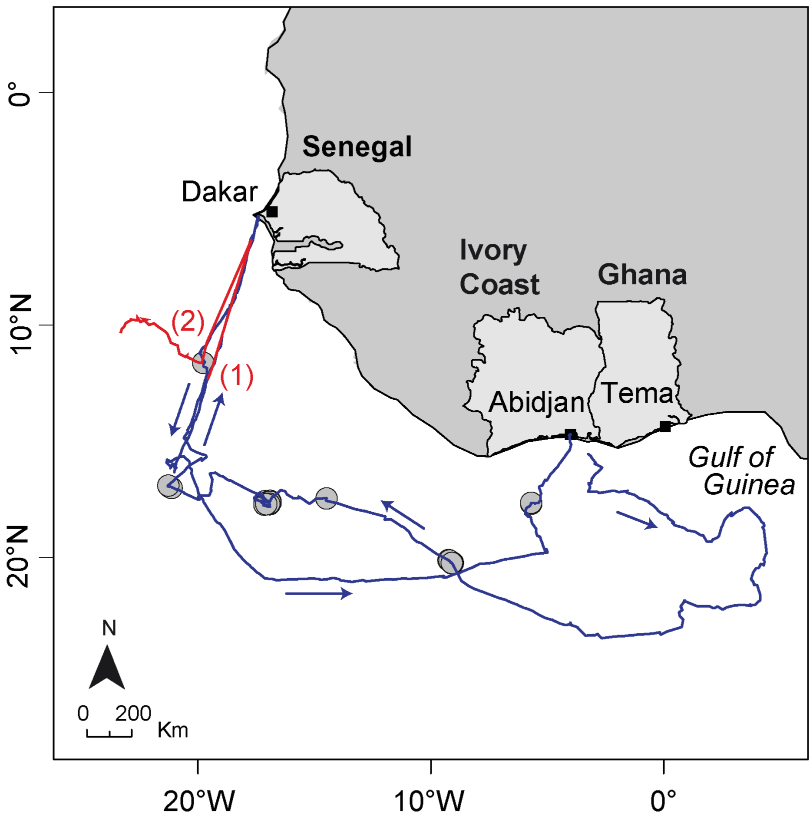


Figure 2.2: Example of vessel (blue line) and buoy (red line) trajectories inferred from VMS and buoy GPS positions, respectively. After leaving the port of Abidjan (black square) the boat heads to the East in the direction of the Gulf of Guinea, before heading to the West in the direction of Dakar and conducting a series of fishing sets (grey dots). The overlap of the buoy and vessel trajectories indicates that the vessel turned on this particular buoy (1) before entering the port of Dakar. The buoy was likely deployed after leaving the port, shortly after performing a fishing set (2).

2.2.3 Construction of the learning dataset

The true state of a subset of the GPS positions available was manually determined using complementary fishery data. Vessels trajectories were inferred from VMS position measurements and superimposed in space and time on GPS buoy trajectories to detect shared pieces of tracks (Figure 2.2). VMS tracks possessing positions close in space (<5 km) and time (<1 d) to GPS buoy positions were initially selected for closer comparison. These “nearby” VMS trajectories were interpolated at the emission times of GPS buoys, and distances between buoys and fishing vessels at identical times were calculated. Original buoy tracks and nearby VMS tracks, spatial separations between the two, buoy speeds, and locations of fishing sets were simultaneously visualized using Matlab (The MathWorks, Inc., 2012). Points of bifurcation between GPS buoy and VMS tracks, as well as the nature of the GPS buoy track preceding and following these bifurcations (e.g., consistently low or high speeds, and sinuous versus straightline tracks), were used to assign “on board” (B) or “at sea” (S) states to individual buoy positions. Geographic locations of the principal tuna landing ports were used to classify positions less than 5 km from a port as “on board” positions. Buoy positions too distant in time (>1 d) and space (>5 km) from any VMS or fishing set data and having speeds that were consistently too large (> 1.5 $m.s^{-1}$) to be considered “at sea” (possible if the buoy was recuperated by a non-French purse-seiner for which we do not have VMS data) were not assigned a class. Variables such as buoy speed or distance to the nearest port, that were used later to build the classification models, were only used as a complementary source of information. For example, it was sometimes difficult to visually determine a transition from “on board” to “at sea”. In such cases, if buoy speed decreased between time t and t+1, then position at time t was assigned a class “on board” and “at sea” at t+1. A total of 19,927 points corresponding to 207 different buoy trajectories were classified using this method (2.3% of the buoy dataset). The majority of this learning dataset consisted of “at sea” positions, with 13.8% of the learning dataset classified as “on board” positions.

2.2.4 Classification model selection

Four binary classification methods were compared for their ability to correctly predict the “at sea” (S) or “on board” (B) state of each dFAD position based on a set of predictor variables characterizing buoy speed, acceleration, time step, water temperature, etc. at each position (Table 2.2). The intended, long-term use of classification models is to optimally classify new dFAD position data received from the fishing companies on

Table 2.2: List of predictor variables considered in the classification models. t-1, t and t+1 represent 3 consecutive positions of buoys over time.

Variable	Formula
Time interval (s)	$Time_{t+1} - Time_{t}$
Time interval before (s)	$Time_{t} - Time_{t-1}$
Time interval change (s)	$Time_{t+1} - Time_{t-1}$
Speed ($m.s^{-1}$)	$Distance_{t,t+1}$ / $Time\ interval_{t,t+1}$
Speed before ($m.s^{-1}$)	$Distance_{t-1,t}$ / $Time\ interval_{t-1,t}$
Acceleration ($m.s^{-2}$)	$2(Velocity_{t,t+1} - Velocity_{t-1,t})$ / $Time\ interval_{t,t+1}$
Heading change (rad)	$Heading_{t,t+1} - Heading_{t-1,t}$
Min distance from a major port (km)	$Linear\ distance_{t-port}$
Water temperature (°C)	$Temperature_{t}$
Water temperature before (°C)	$Temperature_{t-1}$
Water temperature change (°C)	$Temperature_{t} - Temperature_{t-1}$
Water temp. change / interval (°$C.s^{-1}$)	$(Temp_{t} - Temp_{t-1})$ / $Time\ interval_{t-1,t}$

a quarterly basis. As the resulting large dFAD dataset will be used by multiple individuals having disparate levels of statistical expertise, it is desirable to identify the simplest, most-computationally-efficient classification method that can accurately predict buoy state. Therefore, although one would expect that more sophisticated classification methods (e.g., random forests) will perform best, simpler methods were also tested to assess trade-offs in terms of accuracy and computational time associated with different levels of model complexity.

The methods tested were: a speed filter (VEL), multiple logistic regression (MLR), artificial neural networks (ANN) and random forests (RF). These methods range from fairly intuitive approaches (VEL, MLR; Dreiseitl and Ohno-Machado, 2002; Bertrand et al., 2008) to sophisticated, 'black-box' models (ANN, RF) capable of representing complex interactions between variables without making assumptions regarding the distribution of the classification variables (ANN, RF;Breiman, 2001; Lee et al., 2005), and of coping with noisy data and correlated classification variables (RF; Breiman, 2001; Cutler et al., 2007). In the case of the RF method, often described as robust to correlation among predictors (Cutler et al., 2007), these may however induce a biased interpretation of the contribution of such variables to the model (Nicodemus et al., 2010; Strobl et al., 2008, 2009). As our objective was not to build a good explanatory model but a good classifier of GPS buoy positions, we chose to include all available classification variables, regardless of their possible correlation. This is further discussed in Appendix A.2.

2.2.5 Configuration of classification models

The performance of the best model configuration for each of the 4 classification models was evaluated using cross-validation. The learning dataset was randomly split 100 times into a training dataset (used for model calibration) and a validation dataset (used to evaluate model performance) each containing 50% of the learning trajectories. During the calibration phase, each of the 100 training datasets was used to build an optimal version of the MLR, ANN, and RF models.

The full list of predictor variables can be found in Table 2.2. With the exception of the VEL model, which was manually calibrated based on the maximum "at sea" speed observed in the learning dataset, all model calibrations and predictions were carried out using R version R.2.14 (R Core Team, 2012) with the caret package (version 5.15-023, Kuhn, 2008) and its train function. The train function uses a bootstrap approach, with 200 iterations, to determine an optimal set of model configuration parameters (i.e., parameters that affect model structure and complexity, such as the number of hidden neurons in the ANN model; Table 2.3). For each of the 100 training datasets described above, 200 different random subsets are generated by resampling with replacement the training dataset, and then each given classification method is calibrated for each subset

Table 2.3: Classification methods used to separate 'at sea' and 'onboard' positions of the buoys.

Method	Features of interest	References	Parameters
Multiple Logistic Regression (MLR)	intuitive, white-box	Dreiseitl and Ohno-Machado 2002	Weight decay w
Artificial Neural Network (ANN)	no assumption, complex non-linear relationships	Dreiseitl and Ohno-Machado 2002 Joo et al. 2011	Weight decay w Size s
Random Forest (RF)	no assumption, complex non-linear relationships, robustness to overfitting	Breiman et al. 2001 Cutler et al. 2007	Randomly chosen variables mtry

using all possible combinations of model-configuration parameter values. For each subset, the accuracy rate (fraction of correct predictions) and the Kappa statistic (which measures to what degree the prediction will be repeatable and reproducible) are computed using the remaining, unused part of the original training dataset. The set of configuration parameter values that maximizes the mean accuracy and mean Kappa among the 200 bootstraps is used to calibrate the given classification model to the entire training dataset. In the end, this procedure produces 100 optimized predictive classification models, one for each training dataset. The train function internally calls a different model for each classification method: the MLR and ANN method of the nnet package (version version 7.3-1, Venables and Ripley, 2002), and the RF method of the RandomForest package (version 4.6-6, Liaw and Wiener, 2002).

As the learning dataset is imbalanced in favour of “at sea” positions (86.2%), we also considered two approaches for correcting for imbalanced data: (1) using an optimal threshold other than 0.5 as the minimum probability required to declare a point “at sea” and (2) forcibly balancing the training dataset before model calibration. The first approach used maximization of sensitivity plus specificity (Jiménez-Valverde, 2012) to determine a threshold for all classification methods other than VEL. The second approach was applied to the RF model as the RF algorithm used possesses an internal procedure to rebalance data. As neither of the two approaches improved overall model classification performance, they are not discussed further here, but details can be found in Appendix A.1.

2.2.6 Comparison of classification methods

The validation phase consisted of using the models calibrated on the 100 training datasets to predict the class of the positions in the corresponding 100 validation datasets. Classification model performance was evaluated through a balance of 5 indicators of performance based on minimization of the misclassification of “at sea” and “on board” positions (“position based” indicators, Table 2.4) and based on the ability to minimize the incorrect segmentation of trajectories (when sequences “at sea” - “on board” or “on board”- “at sea” occur along a trajectory) due to classification errors (“trajectory based” indicator, Table 2.4). 100 values of each indicator were calculated over the cross-validation procedure to obtain a distribution of their values. Pairwise comparisons of the performance of the models were then performed based on two sided t-tests ($\alpha = 0.05$) using the speed filter (VEL) as the reference method. During this comparison phase, we made sure that each

Table 2.4: Definition of position-based and trajectory-based indicators of performance for classification methods

Type	Indicator	Formula	Description
Position-based	Error rate	$FB + FS / N_{positions}$	Accuracy of the classifier (no distinction of class)
	Precision	$TS / S_{predicted}$	Repeatability and predictive power
	True Sea Rate	$TS / S_{observed}$	Sensitivity. Ability to detect at sea positions
	False Sea Rate	$FS / B_{observed}$	1 – Specificity. Ability to detect on board positions
Trajectory based	Segmentation rate	$'BSB' + 'SBS' / N_{trajectories}$	Inappropriate segmentation of the trajectories

S: at sea; B: on board; TB: True Boat; TS: True Sea; FB: False Boat i.e. the number of positions incorrectly predicted to be on board; FS: False Sea, i.e. the number of poistions incorrectly predicted to be at sea; Nsegments: number of $_{segments}$ over a GPS buoy trajectory; obs:observed; pred: predicted single position was correctly assigned a class “at sea” or “on board” through position based indicators such as the True and False Sea Rates (Table 2.4).

However, as our objective was not only to correctly classify each single position but also sequences of “at sea” and “on board” positions, we ensured that improving position based indicator values was not inducing an over-segmentation problem. For this purpose, we put more emphasis on decreasing the segmentation rate than on increasing the TSR or decreasing the FSR as we considered less important to correctly classify a few isolated positions than to correctly capture a whole section of “at sea” or “on board” positions.

2.2.7 Trajectory post-processing

The classification methods described above do not take into account the temporal relationship between successive buoy positions, but rather treat each position as independent of all others. This assumption can result in incorrect sequences of “at sea” and “on board” classes inconsistent with the fishing process. For instance, a sequence of the type ‘BSB’ is unrealistic as buoys are unlikely to be left at sea for only a few hours. Hence, post-processing of the outputs from the best classification model was performed to reclassify buoy positions in short “at sea” trajectories as being “on board” positions.

During this procedure, we varied the maximum number of isolated, consecutive “at sea” positions to be reclassified as “on board” positions. For each maximum length for reclassification, we recalculated performance indicators (Table 2.4). Results with and without post-processing of predictions from the RF model were compared using a two-sided t-test of the indicators of performance ($\alpha = 0.05$).

2.2.8 Model application and data analysis

The best classification model including post-processing corrections was applied to the full buoy position dataset, and “at sea” and “on board” predictions were made for each position. Model predictions were then employed to detect potential fishing set positions assuming that transitions from “at sea” to “on board” potentially correspond to the retrieval of a dFAD and its buoy from the sea. Spatial patterns in fishing positions predicted by the model were compared to observed fishing positions as declared in fishing vessel logbooks. Note that predicted retrieval locations include some operations on floating objects that do not correspond to a fishing set (e.g., maintenance, buoy displacement to a different location or foreign buoy replacement), as well as buoys lost at sea due to the sinking of the attached floating object. 1-degree gridded density maps of observed and predicted fishing positions were created, and qualitative and quantitative comparisons between the two were carried out. These analyses were used both as a validation of the classification method and as a means to identify zones where endpoints of dFAD trajectories may not be related to fishing sets. Quantitative comparisons consisted of computing the Spearman correlation coefficient of observed and predicted densities in all grid cells containing at least one observed or predicted fishing set position.

Model results were then used to: (i) characterize dFAD trajectories (i.e. distance and time at sea), (ii) describe the spatial distribution of dFADs (using 1-degree gridded density maps in the Atlantic and Indian Oceans during 2007-2011), and (iii) calculate the fraction of time buoys spend outside historical fishing grounds, presumably representing ineffective fishing effort. In addition, possible dFAD beaching events were identified using the original, unclassified dataset by series of repeated geographical positions. The unclassified dataset was used to avoid any possible confusion in the classification algorithm between at port and beached positions. We assumed that at least 3 repetitions of the same position were necessary to identify a possible beaching event as occurrence of 2 repeated positions is known to be related to failures to correctly capture a GPS signal (see section Buoys positions data and pre-processing). Final results were obtained using 2 successive filters on these potential beaching-event positions. First, we eliminated positions located within 10 km of a port, assuming that these are likely to be simply fishing vessel anchorage points. Second, we eliminated positions located more than 5 km from land (accounting for 5.7% of all potential beaching events). These later “stopping points” may represent real shoaling events on offshore, shallow-water areas, but were considered more likely to be due to something other than shoaling, and, therefore, results were calculated with and without these points.

‘Ineffective’ dFAD fishing effort was described through 1-degree gridded density maps of buoys drifting outside historical dFAD fishing grounds, the proportion of fishing sets predicted outside fishing grounds, and the fraction of time a given dFAD spent drifting outside fishing grounds. Two definitions of historical fishing grounds were considered: the spatial distribution of catch under floating objects between 2006 and 2012 based on (1) the French fleet only and (2) all operating fleets. Fishing grounds of the corresponding fleet(s) were defined as all one degree grid cells containing at least one purse-seine fishing set.

2.3. Results

2.3.1 Classification model performance and selection

A speed threshold of 1.3 m.s-1 produces a classification of “at sea” positions with a True Sea Rate (TSR; see Table 2.4 for definitions of model performance statistics) of 99.3%. However, the False Sea Rate (FSR) of 43.3% indicates that almost half of the “on board” positions are classified as “at sea” (Table 2.5). Compared with the VEL model, True Sea Rate does not noticeably increase or decrease for any of the classification models tested in this study. For the MLR, ANN and RF (without and with post-processing of outputs) models, the error rate, the False Sea Rate and the segmentation rate all decrease while the precision increases. Among these indicators, the most important improvement is obtained for the False Sea Rate, which decreases to 24.2%, 17.8% and 12.3% in the MLR, ANN and RF (without post-processing) models, respectively. The segmentation rate for these 3 models decreases from a 143% increase in state transitions (i.e., predictions of ‘BS’ or ‘SB’ transitions relative to the true rate in the learning dataset) for VEL to +90.8, 93.2%, 62% for MLR, ANN, RF models respectively. Though the MLR, ANN and RF models produce similar values for True Sea

Table 2.5: Performance of the classification models, as a mean of the indicator on the 100 cross-validation for the VEL, MLR, ANN and RF method

Performance indicator	VEL	MLR	ANN	RF
Error rate (%)	6.6	3.8 [-2.8;-2.7]	3.4 [-3.3;-3.1]	2.6 [-4.1,-3.9]
Precision (%)	93.4	96.2 [2.7;2.9]	97.1 [3.7;3.8]	98.0 [4.5;4.7]
True Sea Rate (%)	99.3	99.5 [0.1, 0.18]	99.0 [-0.4;-0.3]	99.0 [-0.4;-0.2]
False Sea Rate (%)	43.4	24.2 [-19.6;-18.7]	17.8 [-25.9,-25.1]	12.3 [-31.2,-30.6]
Segmentation rate (%)	142.9	90.8 [-54;-49.9]	93.2 [-52,5;-46.5]	59.3 [-86.6;-80.2]

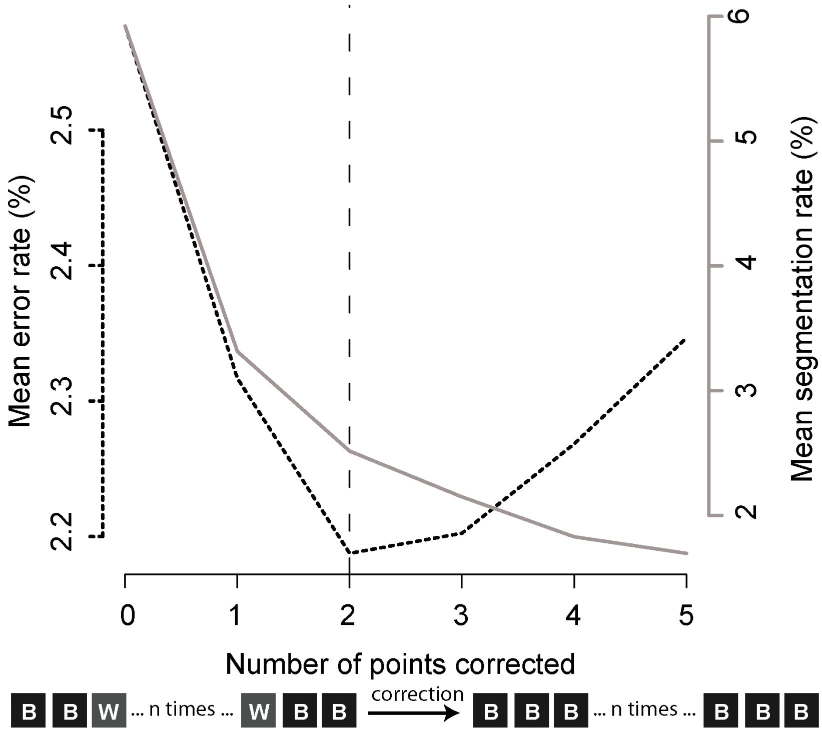


Figure 2.3: Mean error and segmentation rates over 100 cross-validation datasets for correcting between 1 and 5 isolated "at sea" positions.

Rate, all other indicators of performance indicate that the RF model performs considerably better than the MLR and ANN models, especially with regards to False Sea Rate, precision and segmentation rate (Table 2.5). Because of its superior performance, the RF model was chosen as the best classifier for dFAD trajectory data.

Replacing RF predicted classification sequences of the type BSSB (i.e. two, isolated points classified as "at sea") with BBBB considerably improves performance indicators. Error rate drops from 2.6% to 2.2% on average for the 100 validation datasets (Figure 2.3). This correction also significantly improves all other performance indicators (Table 2.5), notably reducing the segmentation rate from 60% to 25%. Using the RF model with post-processing correction, we predict that 15.5% of the full dFAD trajectory dataset consists of "on board" positions, showing the importance of separating "at sea" and "on board" positions before analysing patterns of dFAD use.

2.3.2 Spatial patterns in dFADs

Overall patterns of potential dFAD fishing sets derived from the classified buoy data (i.e., ending points of "at sea" trajectories) are similar to the spatial pattern of fishing sets derived from vessel logbooks from French purse seiners over the period 2007-2011. The cross-correlation Spearman coefficient between observed and predicted spatial patterns of fishing sets is 0.64 ($p < 0.001$). More importantly, the main features and hotspots of the spatial distribution are correctly identified (Figure 2.4). dFAD-associated fishing sets, as declared by the skippers, are mainly concentrated from the Senegalese to the Gabonese coasts in the Atlantic Ocean, while they are mainly observed off Somalia and in the Mozambique Channel in the Indian Ocean. Predicted dFAD fishing grounds cover broader zones in the Indian and Atlantic Oceans than logbook data, extending into the western Atlantic and eastern part of the Indian Ocean where few fishing sets by

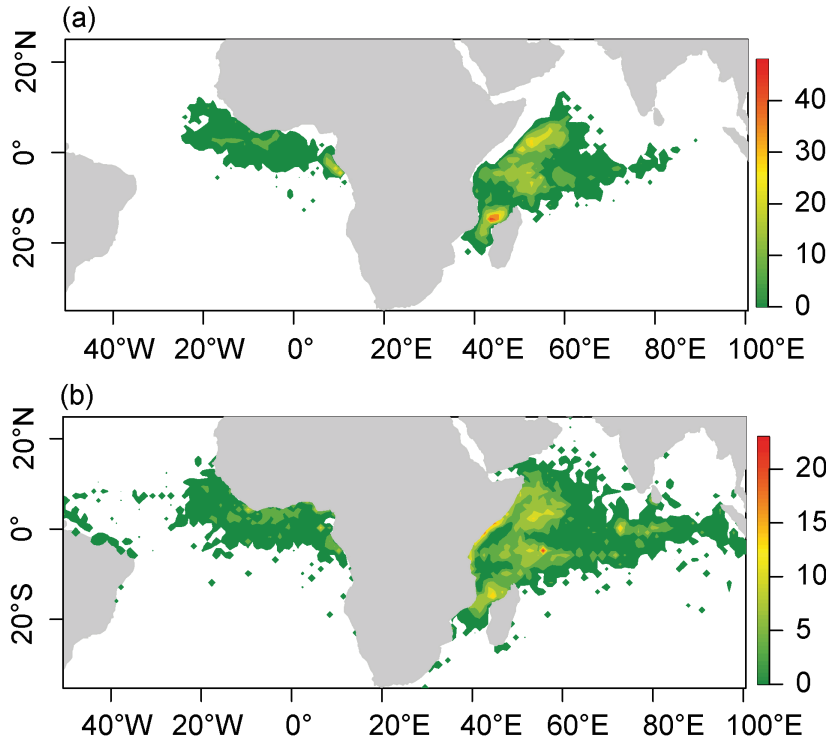


Figure 2.4: Smoothed mean densities of observed (as declared in logbooks, a) and predicted dFAD fishing sets (as derived from the corrected RF outputs, b) for the period 2007-2011. Densities were calculated on a 1° grid and smoothed using the two dimensional density estimation function kde2d of the MASS package in R (bandwidth chosen according to the rule-of-thumb provided in the function bandwith.nrd).

French purse seiners occur. These differences may be attributable to deactivation of GPS buoys for dFADs that are drifting too far from fishing grounds, sinking of dFADs or dFAD use by fishing fleets for whom data is not available (e.g., artisanal fleets). However, zones of predicted fishing sets that are not observed in French purse seine logbook data generally have low densities of predicted dFAD trajectory endpoints, and principal fishing zones predicted from dFAD trajectories are largely consistent with logbook fishing sets.

2.3.3 dFAD time and distance at sea

Predicted "at sea" portions of dFAD trajectories are on average 39.5 days long (standard deviation (SD) of 61.6, standard error (se) of 0.4), corresponding to a mean piecewise-linear drift distance of 1225.8 km (SD 1829.3, se 12.05), with both statistics showing important differences between oceans, years of release and months of recapture (Figure 2.5). In the Atlantic Ocean, both interannual and seasonal variability in time and distance-traveled at sea are important. Mean time at sea is 47.8 d (SD 69.6, se 0.89) with a minimum predicted time length of 1 hour and a maximum of 825 d (i.e. more than 2 years). Atlantic interannual variation in

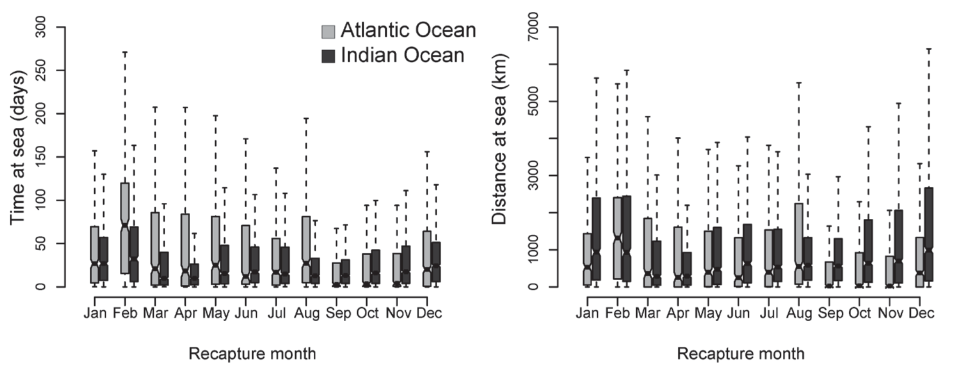


Figure 2.5: Time (a) and distance (b) at sea per ocean (in d and km) as a function of recapture month.

time at sea is important, e.g. with an average time at sea of 72.4 d in 2009 (SD 80.1, se 2.73) and 34.6 d in 2011 (SD 57.8, se 1.16). From February to November, days spent at sea decrease from 81 d on average (SD 82.9, se 3.6) to 29.9 d (SD 54.2, se 2.36). These monthly times at sea were significantly different (two-sided F test comparison of variances, α=0.05: p-value<0.001). During the period September-November, distance at sea is the shortest of the year, with dFADs travelling 664.6 km (SD 1322.4, se 57.55) in November versus 1627.4 km (SD 1824.3, se 78.37) in February. Again, differences between months are significant (two-sided F test comparison of variances, α=0.05: p-value<0.001). Note that the apparent high turnover rates of dFADs during the period September-November may also be related to frequent transfers of GPS buoys (when purse seiners replace a buoy found on a foreign dFAD with one of their own buoys).

In the Indian Ocean, time at sea (36.6 d, SD 58.2, se 0.44) is on average shorter than in the Atlantic Ocean, although the distance travelled at sea (1285.5 km, SD 1897.1, se 14.58) is higher. Variations also occur between years but with a lower magnitude than in the Atlantic Ocean, ranging from 32.6 d (SD 51.6, se 0.89) in 2011 to 45.7 d (SD 53.3, se 0.92) in 2008. dFADs retrieved in March-April and August-September generally spend less time at sea than those retrieved from December to February, with the shortest time at sea obtained for the month of April (28.4 d, SD 51.8, se 1.38) and the longest for the month of February (53.5 d, SD 73.0, se 2.43). These monthly times at sea were significantly different (two-sided F test comparison of variances, α=0.05: p-value<0.001).

2.3.4 Lost GPS buoys

Putative beaching events, identified by positions that repeat at least three times far from a port, occur in 26.4% of the GPS buoy tracks, corresponding to 10.5% of the "at sea" trajectories in the dataset (a lower percentage because GPS buoys have more than one "at sea" trajectory). When distance to the coast is

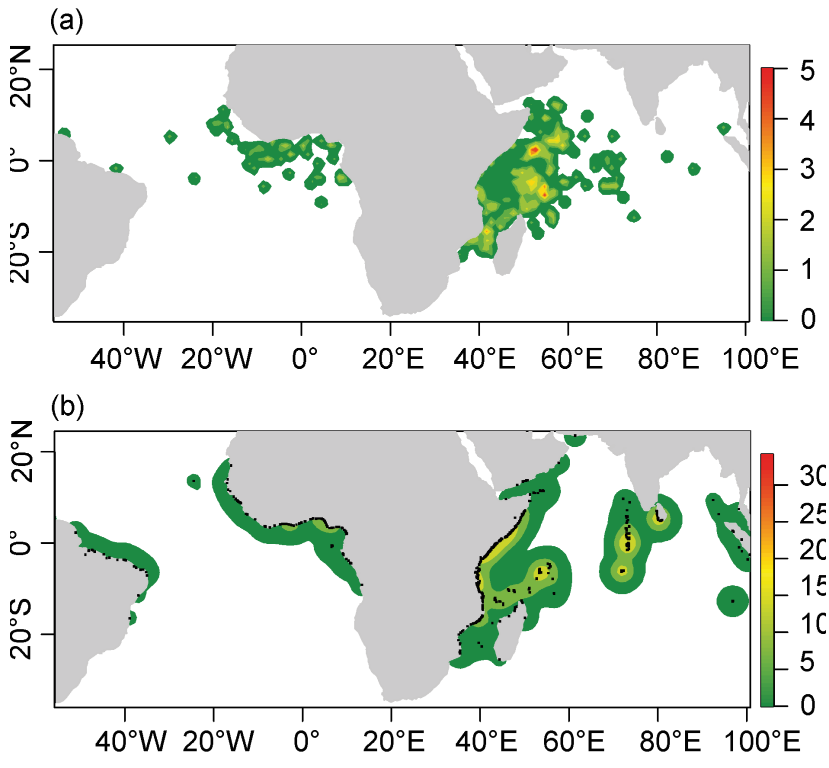


Figure 2.6: Smoothed densities of dFAD beaching events (a) and their corresponding deployments positions (b). Black dots correspond to individual beaching positions.

also taken into account, the percentage of beached at sea trajectories decreases to 9.9% (i.e., 5.7% of all putative beaching events occurred more than 5 km from the coast). More potentially beached GPS buoys are detected in the Indian Ocean (1328) than in the Atlantic Ocean (1128), in line with the larger number of dFADs deployed by the French fleet in this ocean. In the Atlantic Ocean, potentially beached buoys tend to concentrate in the Gulf of Guinea but some buoys also cross the entire ocean to strand on the Brazilian coast (Figure 2.6a). These dFADs have been deployed “at sea” off Abidjan, Tema, in the Gulf of Guinea and off Gabon (Figure 2.6a). In the Indian Ocean, beaching events occur over a wider set of zones, with Somalia, the Seychelles, the Maldives and Sri Lanka being the most important. Beaching events also occurred within the Marine Protected Area of the Chagos Archipelago (Figure 2.6b). Their deployment positions are mainly located around the Seychelles, in the Mozambique Channel and off Somalia (Figure 2.6b). As for the buoys found potentially stored at port (that are not part of the previous numbers), 7.3% are found far from a major landing port (Abidjan, Ivory Coast; Dakar, Senegal; Tema, Ghana; Victoria, Seychelles; Port Louis, Mauritius; Saint-Denis, Reunion Island; Diego Suarez, Madagascar; or Mombasa, Kenya), with this proportion being slightly higher in the Atlantic Ocean than in the Indian Ocean, consistent with the presence of more ports that are not used for tuna landings in the Atlantic Ocean. These “at port” buoys may correspond to buoys found by vessels that do not belong to the French purse seine fleet. Therefore, they could be considered as lost for the French fleet, as purse seiners rarely have the possibility to retrieve buoys from such minor ports (when purse seiners from other major, industrial fleets find and replace French buoys with one of their own buoys, the French buoy is generally returned to the docks of one of the major ports).

2.3.5 ‘Ineffective’ dFAD effort

A total of 6,563 GPS buoys (i.e. 68.4% of the dataset) were found to be drifting outside French fishing grounds (see Figure 2.4a for the location of French fishing sets on dFADs) at least once during their whole

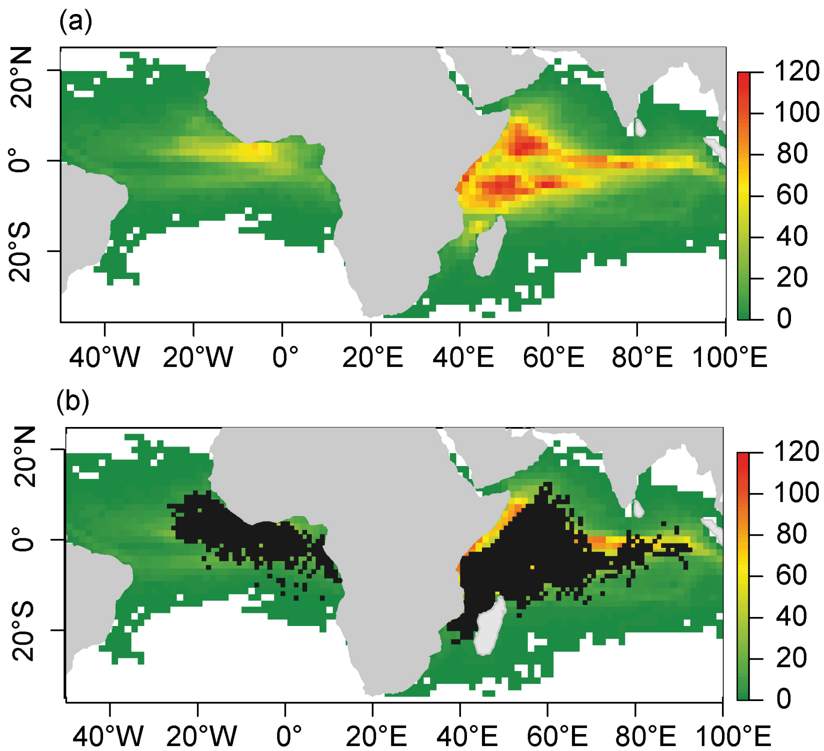


Figure 2.7: Mean yearly dFAD density (a) and ineffective dFAD effort (b) for the period 2007-2011. Black areas correspond to 1° grid cells where at least one French or Spanish fishing set has occurred over the period 2006-2012.

"at sea" set of trajectories. By comparison, with fishing grounds based on all fleets for the period 2006-2012 (Figure 2.7b) , this number decreases to 5,420 (57% of the dataset). Though the average fraction of total drift time spent outside fishing grounds is relatively small (3.05% for French fishing grounds; 2.2% for all fishing grounds), for some buoys, the time spent outside fishing grounds is extensive. For example, 20.6% of the drifting trajectories spent less than 50% of the time inside French fishing grounds (8.5% if all fishing grounds are considered). Main zones of dFADs travelling outside French fishing grounds are the area around the port of Tema (Ghana) and a large area east of the fishing ground in the Atlantic Ocean, as well as the Maldives, the eastern coast of Sumatra and the area adjacent to the coast of Somalia in the Indian Ocean (Figure 2.7).

2.4. Discussion

Our analyses of the spatio-temporal distribution of dFAD trajectories both complement existing data on tuna fishing activities, as well as provide new, previously-unavailable insights into purse seine strategy and potential impacts of fishing. In particular, we provide for the first time information on the principal characteristics of dFAD use (i.e. density, turn-over, travelled distance, time at sea, and variability in time and space), essential for improving the monitoring and management of fishing effort exerted by purse seine fleets in the Atlantic and Indian Oceans. Though our dFAD buoy positions are characterized by irregular time-steps, occasional abherant data and mixing of "at sea" and "on board" states, the classification methodology described here is able to reconstruct "at sea" trajectories with a relatively high level of accuracy. The best classification methodology, consisting of a random forest binary-classification model followed by post-processing to remove short "at sea" trajectories consisting of just one or two "at sea" positions, has an error rate of just 2.2%. Nevertheless, 25% more "at sea" trajectories are predicted than are observed, suggesting that improvements to reduce the trajectory segmentation rate are still possible (see end of Discussion).

Seasonal variation in dFAD mean times at sea are consistent with known patterns of purse seine fishing activity (Floch et al., 2012a, 2012b; Kaplan et al., 2014), though variability in trajectory time length is very high among "at sea" trajectories. In both oceans, during periods when purse seiners concentrate on dFAD-fishing, times at sea are shorter than during seasons when fishers mainly target free-swimming tuna schools, suggesting higher rates of dFAD deployments and buoy transfers during these periods. Times at sea are shorter in the Indian Ocean than in the Atlantic, but the reverse is true for distance travelled by dFADs. These results are potentially explained by the stronger ocean currents and ocean variability in the Indian Ocean (e.g., in areas off Somalia), than in Atlantic fishing grounds (Picaut, 1984; Schott et al., 2009). They may also be explained by differences in the design of dFADs between oceans, with the length of the net hanging down beneath the bamboo raft reaching up to 70-100m in the Atlantic Ocean compared to only 30-50m in the Indian Ocean (Franco et al., 2012). The former is considered to reduce distance travelled for Atlantic Ocean dFADs due to increased drag from slow-moving water masses below the thermocline (Dagorn et al., 2013). Finally, differences in time at sea may be related to differences in concentration of purse seiners on fishing grounds that reduce the probability of a raft to be stolen and its buoy to be transferred, thereby increasing "apparent" time at sea in the Atlantic Ocean. High variability among "at sea" trajectories is consistent with the unpredictable nature of dFAD use: dFADs may be rapidly stolen by other vessels, drift for longer or shorter periods before aggregating tuna, or drift outside fishing zones but continue to be monitored for months by skippers.

These initial results on time and distance travelled at sea form a foundation that could be used to model dFAD trajectories, understand the mechanisms underlying these spatio-temporal differences, and hopefully develop management strategies to limit negative impacts on pelagic ecosystems. For example, if the time a given dFAD spends at sea results in changes in catch, bycatch levels or higher probabibilities of ghost fishing (see below), restrictions such as a minimal or a maximal time at sea could potentially be implemented. Distance at sea is also crucial to test the efficacy of spatialized management tools. For example, if dFADs travel a long distance from their deployment position, and tuna remain "trapped" in the array of moving dFADs, they may be extracted from closed areas to be fished elsewhere. These results may also be useful for assessing potential for dFADs to act as ecological traps for tuna, disturbing normal tuna behaviors and leading to reduced survival or growth (Hallier and Gaertner, 2008; Marsac et al., 2000).

With the objective of identifying "ineffective" dFAD fishing effort, we measured the proportion of time "at sea" trajectories occuring outside established fishing grounds. A large proportion of dFADs travel outside fishing grounds during part or all of the time spent drifting at sea, with only 32.3% spending 100% of the time inside French fishing grounds (45.2% if all fleets are considered). Of the dFAD trajectories that are found to be always travelling outside French fishing grounds, 27.9% are inside fishing grounds based on all fleets, and, therefore, this fishing effort may eventually be exploited by non-French industrial fishing fleets. In some cases, such as dFADs passing through the Somali EEZ, these dFADs may be recovered at a later date elsewhere. In others, such as dFADs west of 30°W or east of 80°E, these floating objects are unlikely to be recovered by purse seiners. In such cases, they may represent ineffective or lost fishing effort, or they may eventually be used by other tuna fisheries (e.g., artisanal fisheries of coastal states) in the region. It is unknown what impact these drifting objects may have on the pelagic environment, but some authors have hypothesized that they may represent an ecological trap for tuna and other pelagic species, affecting fish condition, growth and mortality, and moving fish schools outside of prime habitat areas (Hallier and Gaertner, 2008; Jaquemet et al., 2011; Marsac et al., 2000). In addition, active or abandoned dFADs could result in high ghost fishing mortality of turtles and sharks through entanglement in the netting that hangs underneath the rafts (Anderson et al., 2009; Filmalter et al., 2013; Fossette et al., 2014; Gilman, 2011). Modifications in the design of dFADs to reduce risks of entanglement without decreasing their capacity to aggregate tunas have been proposed and recently implemented for the European purse seine fleet (Franco et al., 2012; ISSF, 2012b). Defining purse seine dFAD-fishing effort as directly proportional to the density of dFADs is of course simplistic, but provides a useful alternative to conventional measures of fishing effort, such as vessel search time or number of fishing sets, which are not capable of estimating fishing impacts that occur in the absence of fishers.

Another important question regarding the use of dFADs is what is the eventual fate of lost buoys, and in particular, what impact beaching events may have on coastal environments via their contribution to coastal marine debris. Given that dFADs generally include a significant subsurface structure, including filaments up to 70m in length (Franco et al., 2012), this contribution may be non-negligible. Our analyses indicate that a non-negligible fraction (9.9%) of dFAD deployments (inferred from "at sea" trajectories) do eventually end up beached. Given estimates of about 15-20,000 total (Baske et al., 2012) dFADs annually deployed in the two oceans, this would suggest around 1,500-2,000 beaching events per year, with significant portions of these beaching events occurring in potentially sensitive habitat areas, such as the coral reefs of the Maldives Seychelles, or the Chagos (Graham et al., 2013). This number could be even higher, as we consider here only dFADs close to coastlines, whereas dFADs may also be retained on offshore shallow areas (though these are relatively rare in the Atlantic and Indian Oceans). Mitigating for these impacts by avoiding deployment zones and time periods with a high probability of leading to a beaching event may be possible. However, in the Indian Ocean, for example, this would greatly impact fishing activities during one of the most important seasons for the tuna fishery, as beached dFADs are mainly those that are used to prepare for dFAD fishing off Somalia. In this area, the absence of bilateral agreements allowing fishing in Somalia EEZ, the presence of piracy, the strength of the currents and the intensity of dFAD fishing may explain the high number dFADs lost onshore. This example serves as an illustration of how classified dFAD trajectory data can be used to assess dFAD impacts on fragile marine ecosystems and derive appropriate spatialized management tools based on dFAD deployment zones. Though preliminary, the results obtained could contribute to building a goal-based and transparent criterion for the regulation of dFAD use in time and space.

These results on dFAD spatio-temporal patterns and impacts are all derived from our classification methodology. This methodology is supported by a comparison of four methods to correctly identify “at sea” or “on board” states of dFAD buoys. Ideally, the correct prediction of the class of a given GPS buoy position would have relied on a simple, transparent decision rule. For instance, as purse seiners travel most of the time faster than ocean currents, a dFAD position could be classified as “on board” using an appropriate speed threshold. Though such a speed filter is among the most efficient methods to identify true “at sea” positions (TSR), the false “at sea” detection rate (FSR) for this method is considerable: 43.3%. This high error rate undoubtedly results from periods when the fishing vessel speed is low, for example during fishing sets and potentially at night. Due to this lack of a clear separation between vessel and dFAD drift speeds, more complex decision rules are necessary to classify dFAD positions.

By comparison, the Random Forest (RF) method produces the lowest mean error rate (2.6% versus 6.6% for VEL), lowest False Sea Rate (12.3% versus 43.3% for VEL) and lowest segmentation rate (59.3% versus 142.9% for VEL) of all methods considered, and maximizes the precision while maintaining a very high True Sea Rate. Though drift speed was consistently the strongest predictor of buoy state, other variables, such as acceleration, heading change, water temperature and distance to port, also contributed to the classification algorithm (Supplementary Figure S2.1 in Appendix 2.2). Furthermore, the contribution of these variables to the classification algorithm is often non-linear (Supplementary Figure S2.3 in Appendix 2.2). This explains the significant improvement in performance statistics for the more-sophisticated, non-linear algorithms integrating a full suite of predictor variables, such as ANN and RF. Multiple logistic regression (MLR) performances could have been improved by considering higher-order and interaction terms. Adding such terms would undoubtedly improve performance measures for this method, but there is little a priori basis for choosing the number and maximum order of such terms. Flexible, non-linear classification methods, such as RF and ANN, provide a clear advantage in this sense.

Because of the properties of the four methods tested in this study, the higher performances of the RF could have been anticipated. However, our aim was not only to identify the best classification method, but also to assess trade-offs in terms of model transparency and computational time. In this context, RF produces a non-negligible improvement in performance indicators that justifies its use, though this comes at a computational cost (~3-4 hours computational time to classify all currently-available dFAD position data with RF, versus ~10 minutes for MLR).

Overall, the False Sea Rate indicates that the RF model is highly efficient at identifying when the buoy is drifting at sea. Nevertheless, erroneous splitting of “at sea” or “on board” trajectory segments as a result of misclassifications remains important. For example, the RF model predicts 59.3% more trajectory pieces than observed in the training dataset. Though post-processing to remove very short “at sea” trajectory segments reduces the segmentation rate from 59.3% to 25.2% and improves several other performance indicators, over-segmentation remains non-negligible. Analyses of dFAD trajectories based on considering sequences of “at sea” or “on board”, such as mean time at sea, drift displacement distances or “at sea” trajectory start and end points, are probably biased in our results. This likely partially explains model predictions of very short “at sea” trajectories (e.g., <1 d), as well as putative fishing sets outside of purse seine fishing grounds. Though the correlation between observed and predicted fishing maps is high and important hotspots for dFAD fishing are identified by the RF corrected model, methodological improvements to reduce these biases are an important area for future developments.

There are a number of methodological approaches that may improve our analyses of dFAD spatio-temporal use patterns. One possibility is to use a learning dataset that is balanced in terms of number of “at sea” versus “on board” positions. This approach was tested when developing our classification model, but did not improve results (see Appendix 2.1). A balanced learning dataset is generally desirable in cases where either one prefers to err in favour of the minority class (e.g., when prediction the species distribution of a rare, endangered species) or one believes that the true prevalence of the minority class is higher than what is observed in the learning dataset (Meynard and Kaplan, 2013; Phillips et al., 2009). Neither of these is the case for our dataset. Furthermore, balancing the learning dataset does not contribute to taking into account the temporal relationship between successive observations (see following paragraph).

Performance indicator improvements due to post-processing corrections to the RF model outputs suggest that the sequence of “on board” and “at sea” states in buoy trajectories is informative. Classification methods used here take into account the temporal relationship between position measurements only partially, via several variables (e.g., speed, acceleration, heading change, etc.) that are computed using information at previous and succeeding time steps. If the temporal correlation between the successive positions of a GPS buoy could be measured, integration of these correlations in the classification model may eliminate many extremely short dFAD “at sea” trajectories because such short deployments would be unlikely. Applying standard methods that integrate this type of information for classification purposes, such as Hidden Markov and Hidden Semi-Markov Models (HMM and HSMM), could be an alternative to the RF post-processing solution adopted in this study (Joo et al., 2013). Similar to the discriminative methods examined here, these approaches model the relationship between the probability of being “on board” or “at sea” based on observations, such as the speed and the acceleration at given time. In addition, they consider that the probability of being in a given state at a given time depends on the past states. HSMM, in particular, considers the probability of being in a given state as a function of the time already spent in this state (Joo et al., 2013). The use of HSMMs is not trivial in our case due to the highly irregular timesteps of dFAD trajectories and the high computational costs involved in applying these methods to large datasets. Furthermore, when fishing vessels concentrate in the same area, the probability of a dFAD to be found and its buoy to be transferred after a short drift is higher. Short “at sea” sections of trajectory during periods of intense dFAD fishing may, therefore, be real events and applications of HSMM to these data must take this seasonality into account.

The simplest and most direct solution to these issues would be to increase availability to information on deployment and recovery events of individual dFADs. Though classification schemes like the ones presented here are likely to remain valuable as checks of reported information and as corrections for missing data (e.g., GPS buoy transfers between different national fleets) or data limitations, analytical power would be significantly increased by direct access to data on these dFAD-related fishing activities. Information on dFAD transfers, visits, etc. has been recently added to logbooks of French purse seiners (since January 2013), and therefore it may soon be possible to use these data in combination with the classification and analysis approaches presented here to develop a suite of indicators of spatio-temporal intensity of dFAD use. In this context, the analyses of dFAD use presented here represent a necessary first step to designing effective management strategies for dFAD fishing.

Appendix A1: details on the performance of the RF model

Our FOB learning dataset is heavily imbalanced in favour of “at sea” positions (86.2% of the 19,927 positions). It is at time advantageous to take into account the structure of the learning dataset when building a classification model (Meynard and Kaplan 2012). In our case, this could prevent the classification models from being driven by the “at sea” class and could reduce the prediction errors for the “on board” class. We tested two methods for dealing with an imbalanced training dataset: (1) the use of an optimal threshold probability other than 0.5 for classifying a position as “at sea”, and (2) a “balanced Random Forest” method.

Optimal threshold via maximization of sensitivity+specificity

Separating “on board” and “at sea” GPS buoy positions is a classical binary classification problem. In such problems, it is at times necessary to use a detection threshold of the binary classifier other than the default of 0.5 (meaning that positions with a probability of being at sea greater than 50% are considered at sea). We examined the impact of optimising the detection threshold by maximization of model sensitivity (its ability to detect true positives, in our case the positions “at sea” that are correctly classified as “at sea”, referred to in the text as the “True Sea Rate”) plus specificity (its ability to avoid false positives, in our case the positions “on board” that are incorrectly classified as “at sea”, referred to in the text as the “False Sea Rate”, Jiménez-Valverde 2012). Optimal thresholds were determined using the optimal.thresholds function of the R package PresenceAbsence. We present here the results obtained for the RF model with max sensitivity + specificity,, but maximization of the detection threshold for the two other classification models (MLR and ANN) and/or using a different optimal threshold selection approach (for example, maximization of Kappa) produced similarly small changes in model performance statistics. The procedure was applied over the 100 cross-validation iterations. 100 values of the optimal threshold were obtained and used to calculate the corresponding 100 values of each indicator of performance.

Table A1: Outputs of the RF model, with or without optimal threshold analysis

Performance indicator	RF without correction (threshold=0.5)	RF with optimal threshold (mean threshold=0.46)
Error rate	2.6	2.5 [0.07; 0.2]
Precision	98.0	97.9 [-0.06;0.2]
True Sea Rate	99	99.2 [-0.27;-0.09]
False Sea Rate	12.3	12.9 [-0.98; 0.1]
Segmentation	59.3	55.1 [1.5; 6.8]

Using an optimal threshold did not considerably change performance indicates. Although the other indicators of performance were improved, mean False Sea Rate of the RF was increased from 12.3 to 12.9. Given the limited value of threshold optimisation for the performance indicators we are interested in, we chose to use the default 0.5 threshold in the main text of the manuscript.

Balanced Random Forest

Using the “sampsize” argument in the randomForest function in R, the relative ratio between “at sea” and “on board” data in the training dataset was fixed at values varying from 9:1 (close to what is observed on average in our training dataset) to 1:1, corresponding to a dataset balanced between the “at sea” and “on board” positions.. The 5 indicators of performance were computed for each ratio based on 100 cross-validation iterations. This allowed us to test the effect of a wide range of structures of the learning dataset on the two possible types of misclassifications.

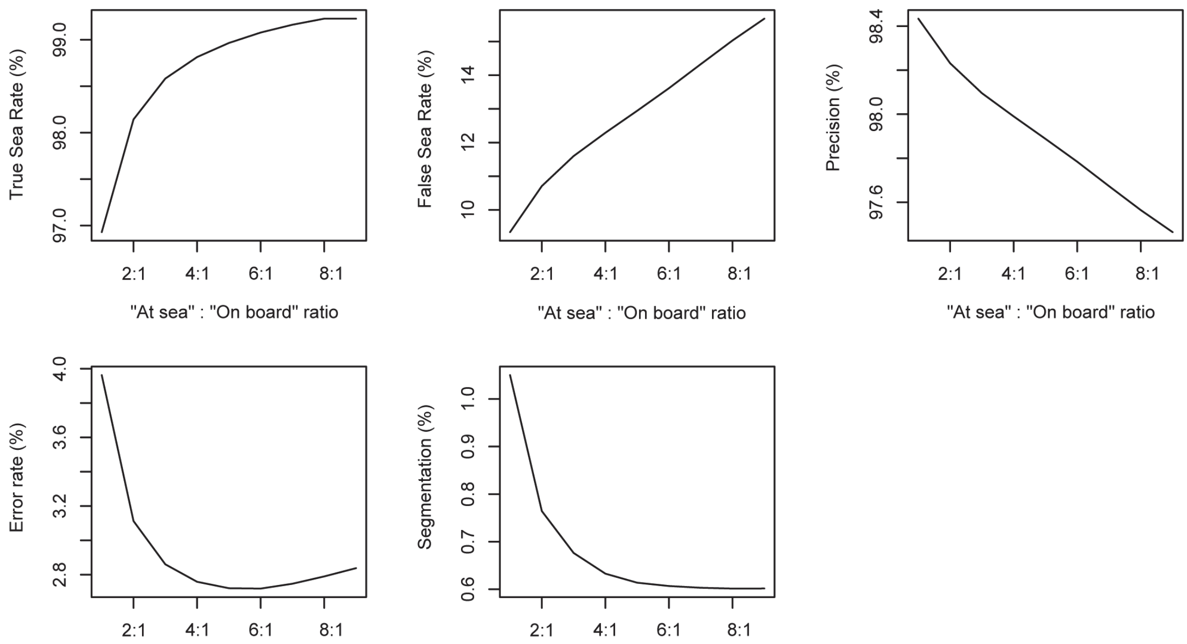


Figure A1: Performance indicators according to changes in the ratio of “at sea” and “on board” positions in the training dataset

Not surprisingly, balancing the training dataset introduces trade-offs between the different performance statistics. The False Sea Rate (FSR) decreases from 15.7% to 9.3% as the ratio “at sea”:”on board” is reduced from 9:1 to 1:1 (Fig. S1). This means that the confusion of “on board” positions with “at sea” positions decreases when the balance of the two classes increases in the dataset. Similarly, balancing the training dataset results in increased precision. However, using a more balanced dataset results in reductions of the True Sea Rate and the overall error rate. Furthermore, reducing the ratio “at sea”:”on board” from 9:1 to 1:1 increased the segmentation rate from 60% to over 100% (Fig. A1).

These results can be used to choose the desired relative costs of each type of misclassification. If our objective had been only to equally correctly classify “at sea” and “on board” positions, a good strategy would have been to choose a ratio “at sea”: “on board” of 2:1 as it greatly improves the False Sea Rate without decreasing too much the True Sea Rate. Another option would be to use a ratio of 5:1, that produces similar Error and Segmentation Rates and slightly reduces the False Sea Rate without decreasing too much the True Sea Rate and the precision. However, our objective was not only to correctly classify each independent position but also to ensure that the sequences of “on board” and “at sea” positions is correct along a given GPS buoy trajectory. For the present study, correctly classifying a few isolated positions is far less important than correctly classifying a whole “at sea” or “on board” section of trajectory. Besides, it is important to keep in mind that the classified trajectories are only useful for their “at sea” sections, as we already have access to vessel trajectories through Vessel Monitoring System (VMS) and “on board” sections only cover a fraction of fishing vessel tracks. As a consequence, overall, balancing the dataset only marginally improves the performance indicators most important for this dataset: True Sea Rate and the segmentation rate. Balancing the training dataset improves the detection of rare events such as “on board” positions , but reduces the ability of the method to detect the more common “at sea” positions. As we are most interested in properly detecting “at sea” positions and maintaining a low segmentation rate, we chose not to balance the dataset in analyses presented in the main text of the manuscript.

Appendix A2: details on the outputs of the RF model

Calibration of the RF model

Table A2: Results of the bootstrap calibration procedure. The optimal value of the parameters has been chosen based on a maximization of the accuracy (minimization of the error rate) obtained for a minimal value of Kappa.

Method	Accuracy (1–%error)	Precision (Kappa)	Tested parameter values	Calibrated parameters
MLR	0.963	0.818	decay= 0, 1e-6, 1e-5, 1e-4, 1e-3	decay=1e-4
ANN	0.968	0.848	decay= 0, 1e-6, 1e-4, 1e-2, 1e-1, 1 size= 1, 2, …, 10	decay=1e-4, size=9
RF	0.978	0.899	mtry= 1, 2, …, 5	ntrees=1500, mtry=4

Interpreting the RF model outputs

Though the focus of the present study is to build a good classifier of “at sea” and “on board” GPS buoy positions, it might be of interest to better understand the structure of the RF model. For example, understanding the contribution of each predictor variable could explain the performances of the RF model, as compared to a simple VEL method. The RF method provides a measure of the relative importance of predictor variables included in the model. The mean decrease in Gini Index tends to indicate that important variables are the speed at the previous time step as well as the speed at time t (Figure A2). However, this metric may not be the best in our case. Figure B2 indicates that some of the predictor variables such as speed variables or temperature variables are correlated or highly correlated (Kendall’s tau coefficient, used for its non-parametric nature, of 0.63 and 0.81 respectively). In such a case, the use of conditional Random Forest and the corresponding mean decrease in accuracy would be more indicated (Strobl et al., 2008; 2009). Indeed, when predictor variables are correlated, mean decrease in accuracy is biased and more weight is given to correlated variables (Nicodemus et al., 2010). Strobl et al. proposed an alternative method for assessing predictor variables importance in the case of correlation. However, as we are more interested in building a good classifier than in interpreting the RF outputs, this may not be a major concern for this study.

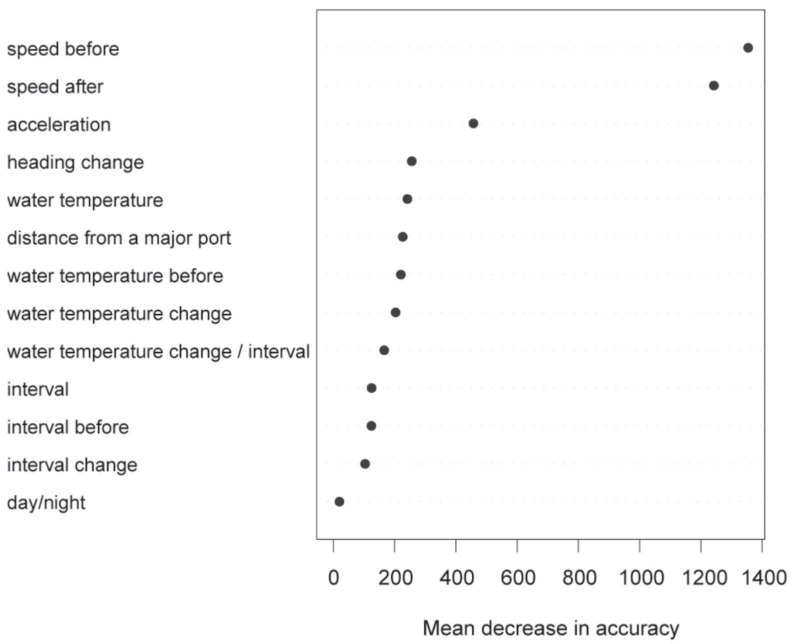


Figure A2: RF model variable importance

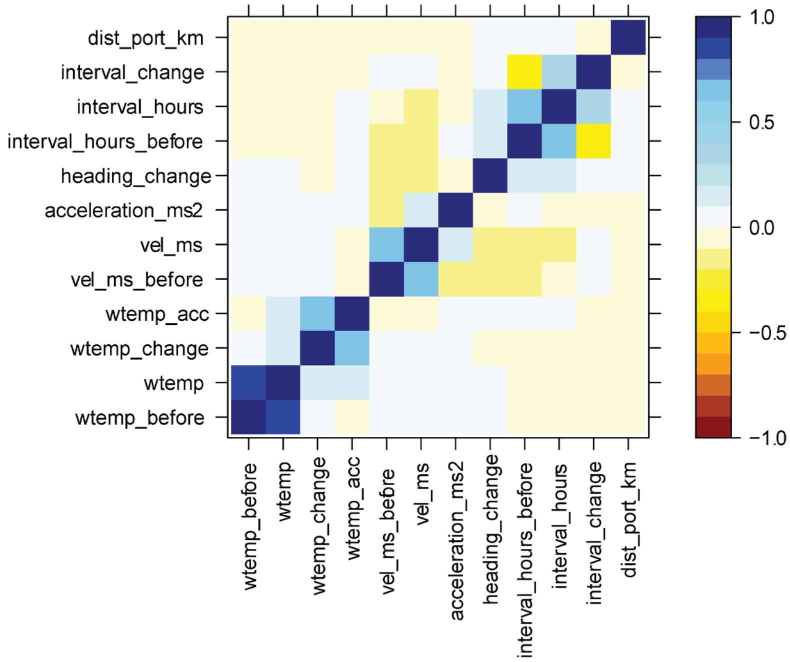


Figure A3: correlated predictor variables included in the RF model (Kendall's tau coefficient)

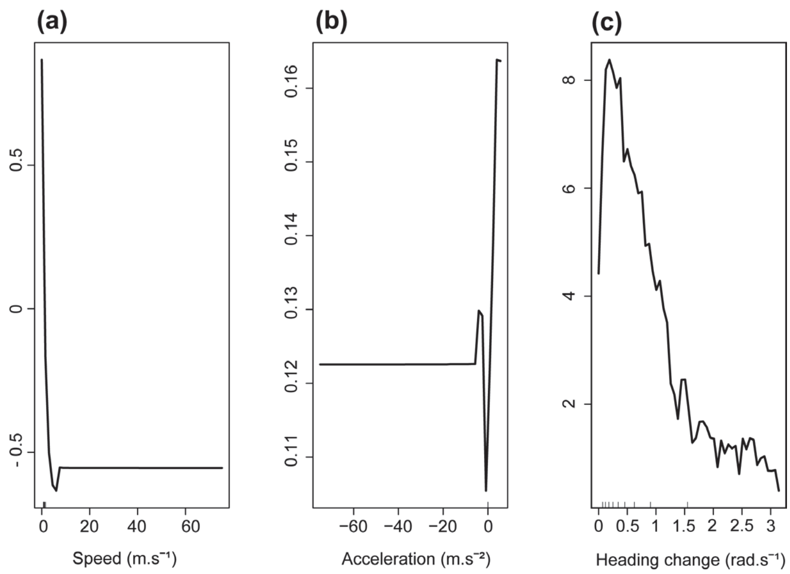


Figure A4:. Examples of partial dependence plots for important classification variables. These plots can assist in the detection of the values used to build the decision rule in the RF model.

Table A3: Results of the RF outputs postprocessing (complement of Figure 2.3)

Performance indicator	BSB	BSSB	BSSSB	BSSSSB	BSSSSSB
Error rate (%)	2.3	2.2	2.2	2.3	2.4
Precision (%)	98.4	98.5	98.6	98.7	98.7
True Sea Rate (%)	99.0	99.0	98.8	98.7	98.6
False Sea Rate (%)	10.2	9.0	8.6	8.2	8.2
Segmentation rate (%)	33.1	25.2	21.5	18.3	17.0

CHAPTER 2:

Massive increase in the use of FOBs by tropical tuna purse seine fisheries in the Atlantic and Indian Oceans

3.1 Objectives of the chapter

For the first time, detailed positions of GPS buoys equipping French FOBs were available. After their pre-treatment to separate “at sea” and “on board” positions, they offered the opportunity to answer many different questions that could be useful for the evaluation and the management of FOB purse seine fisheries. Addressing the question of understanding dFAD and GPS buoy use relied on the combination of this new, previously unavailable source of information (GPS buoy positions) with data that had never been used for such a purpose (observers, logbook and VMS data). Because of the vast amount of data available to answer such questions and their very different nature, fishers’ Local Ecological Knowledge (LEK) was gathered. LEK was used as a valuable complementary source of qualitative information to identify key questions that could be addressed with GPS buoy position data and to guide statistical analyses (Chalmers and Fabricius, 2007; Johannes et al., 2000; Moreno et al., 2007; Neis et al., 1999).

Though the present thesis was mainly based on quantitative data, many of the analyses presented here were inspired by interviews conducted with purse seine skippers of the Indian Ocean in 2013 and in 2015 (see chapter 4 for more details). Such interviews were not a new exercise for tropical tuna purse seine skippers. The cooperation between fishers, fishing companies and scientists has always been strong and skippers have regularly exchanged with scientists since the beginning of the fishery (e.g. Hallier 1988, Gaertner et al. 2000, Moreno et al., 2007a, 2007b, Lopez et al., 2014). Their knowledge of the functioning of the fishery has proved invaluable in many cases. Interviews were conducted with French speaking skippers arriving in the port of Victoria (Seychelles, Indian Ocean) from June to August 2013. 14 skippers (13 French skippers including 2 working for Spanish fishing companies, and 1 Spanish skipper) accepted to exchange with us aboard purse seiners for 1 to 4 hours.

Semi-structured interviews of skippers provided some insights into deployment decision making. We discussed with skippers about the conditions that determined a deployment of a dFAD or of a GPS buoy on a FOB already drifting at sea. They provided keywords (e.g. season, birds, or currents) that were grouped into

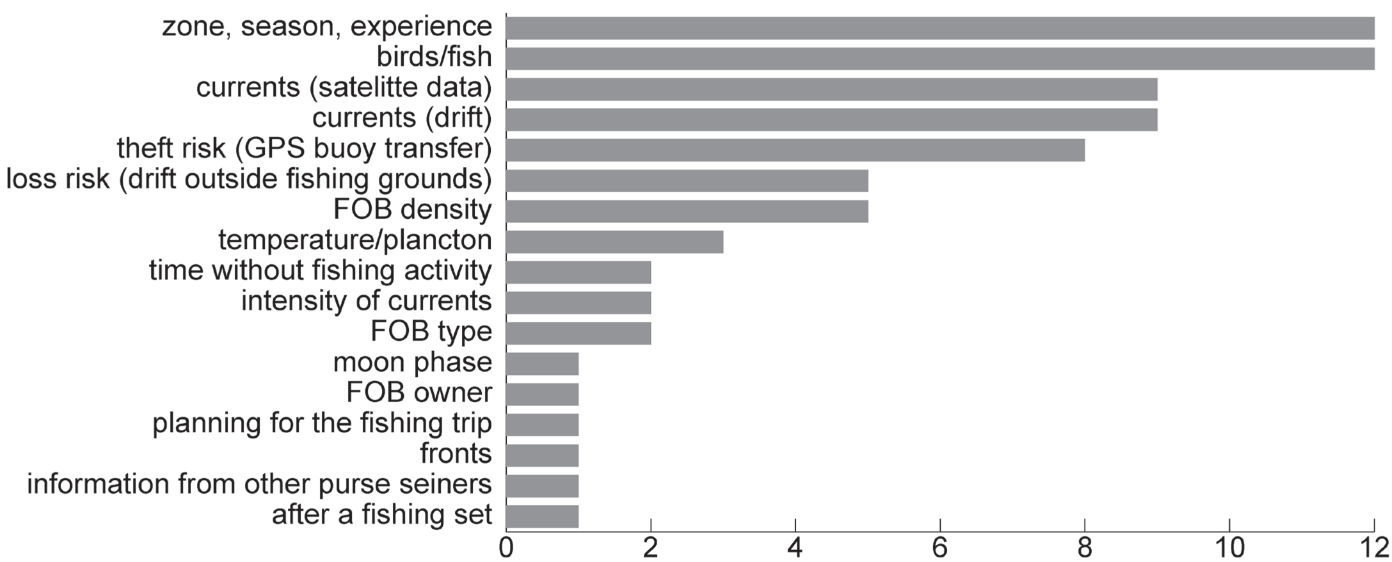


Figure 3.1: important factors used by purse seine skippers to deploy a new dFAD or a GPS buoy on a FOB already drifting at sea

families. The occurrence of these families of keywords in skipper answers was counted to rank their relative importance. The more often a family of keywords appeared, the more important it was considered for a deployment decision. Interviews confirmed the existence of zones and seasons that had been described for the last time during the 1990s (Ariz et al., 1999; Hallier and Parajua, 1992). Skippers also explained that they were taking into account the potential drift and the potential losses of their FOBs by observing the currents, the density of FOBs they had already equipped in the area, and the presence of other fishing vessels who could steal their GPS buoys (Figure 3.1).

During interviews with skippers, changes in the use of FOBs and the fishing effort of purse seiners that are central questions in the present thesis were also discussed. Skippers confirmed that the increasing use of dFADs and GPS buoys was one of the main changes that had occurred in the fishery over the last decades. Their answers further underlined the need for an accurate estimate of the number of FOBs drifting at sea. This was not a surprise, as many authors had already advocated that this was necessary (Dagorn et al., 2013a) but this confirmed the interest of using French GPS buoy data to provide this estimate.

In chapter 2, we therefore combine French GPS buoy data with French and Spanish Observer data and French logbook data to describe skippers' strategies of GPS buoy deployment and to estimate the number of dFADs and GPS buoys drifting at sea.

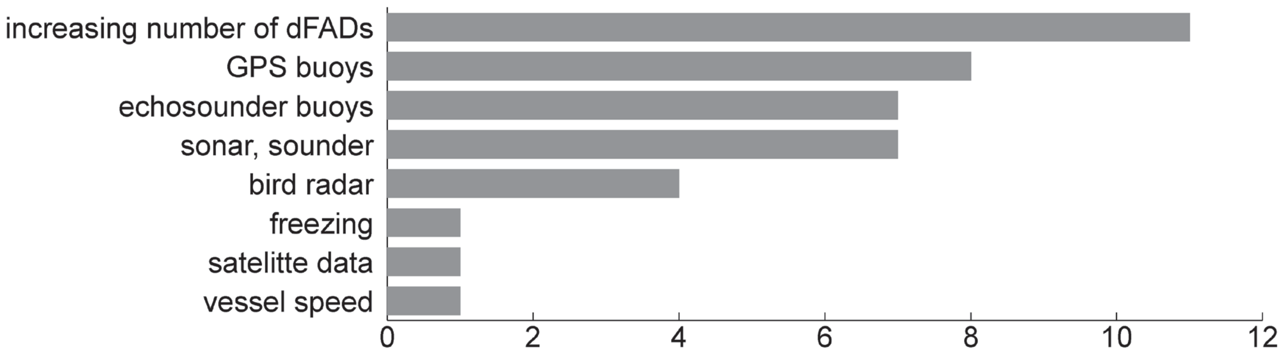


Figure 3.2: main technological improvements of the purse seine fishery according to skippers

3.2 Introduction

Tropical tunas skipjack (Katsuwonus pelamis), yellowfin (Thunnus albacares) and bigeye (Thunnus obesus) tend to associate with objects floating at the surface of the ocean (Kingsford, 1993; Fonteneau et al., 2000; Castro et al., 2002). When tropical tuna purse seiners (PS) began to operate in the Atlantic and Indian Oceans in the early 1960s and 1980s, respectively, they fished on a combination of Free Swimming Schools (FSC) and schools associated with natural floating objects (hereafter termed “logs”). At that time, logs, originating from natural sources, such as river mouths, constituted the main source of Floating OBjects (FOBs) (Greenblatt, 1979). They could be either strict natural floating objects (e.g. wooden debris or marine mammals) or debris of human activities (e.g. pieces of fishing net) (Hallier et al., 1992). During the 1990s, fishers began to deploy large numbers of their own FOBs. These man-made drifting Fish Aggregating Devices (dFADs) generally consist of a bamboo raft covered in old pieces of purse seine net. Support vessels were also introduced into the fishery to assist purse seiners in building, deploying and monitoring dFADs, and also in searching for FSC (Ariz et al., 1999; Ramos et al., 2010).Throughout the 2000s, several technological improvements occurred in the purse seine fishery (Torres-Irineo et al., 2014), including the use of GPS buoys to more accurately locate dFADs and logs, and the introduction of echosounder buoys to monitor the amount of biomass aggregated under FOBs (Lopez et al., 2014).

The development of dFAD-fishing has had several consequences (Dagorn et al., 2013; Fonteneau et al., 2013). First, this increased fishing effort and overall capacity of the fishery by (i) enhancing the aggregation of tropical tunas, including juveniles of yellowfin and bigeye tuna, (ii) reducing search time dedicated to locating tuna schools, and (iii) increasing the fraction of sets with non-zero catch (Ariz et al., 1999; Le Gall, 2000). Secondly, dFADs may have modified the natural habitat of tropical tunas and other species. There are concerns that the increased use of dFADs has modified the dynamics and structure of tuna schools, their feeding ecology and movements (Fonteneau et al., 2000b; Hallier and Gaertner, 2008; Marsac et al., 2000; Ménard et al., 2000). It has been hypothesised that dFADs act as an “ecological trap” by maintaining tunas in suboptimal areas and/or reducing school size (Marsac et al., 2000; Hallier and Gaertner, 2008; Sempo et al., 2013), though evidence for such effects remains limited (ISSF 2014). In addition, FOB fisheries have been shown to have many important impacts on coastal and pelagic ecosystems via increased levels of bycatch and discarding (Amandè et al., 2010, 2012; Hall and Roman, 2013), ghost fishing of sensitive species (Filmalter et al., 2013), and potential damage to fragile ecosystems when lost FOBs end up beaching on coral reefs (Balderson and Martin, 2015; Maufroy et al., 2015 - chapter 1).

Though FOB fishing for tropical tunas has existed since at least the 1990s, it is generally believed that dFAD and GPS buoy use has significantly increased in recent years, leading to potential for significant modifications of pelagic habitats (Hallier and Gaertner, 2008). Despite the recent implementation of dFAD management plans by tuna RFMOs to collect data on dFADs and GPS buoy use (ICCAT Recommandation 14-01; IOTC Resolution 15-08), it is still difficult to verify these assumptions and to measure the magnitude of dFAD use. In this context of growing concerns for tropical tunas and pelagic ecosystems, it is necessary to evaluate how many dFADs are currently drifting at sea and how many dFADs and logs are equipped with GPS buoys (Fonteneau and Chassot, 2014).Prior studies have attempted to provide such estimates, but they were based on limited information, did not separate dFADs from logs, and did not account for spatio-temporal variability in FOB use (Ménard et al., 2000; Moreno et al., 2007; Baske et al., 2012). Furthermore, previous descriptions of dFAD deployment strategies and seasonality in the Indian and Atlantic Oceans date from the beginning of the 1990s (Hallier et al., 1992; Ariz et al., 1999). It is therefore necessary to improve our understanding of the use of dFADs and GPS buoy-equipped FOBs in order to properly manage their use and mitigate their ecosystem and fishery impacts.

Our objectives here are to describe when, where and how many dFADs are deployed by tropical tuna purse seine fisheries in the Atlantic and Indian oceans. We use position records from the period 2007-2013 of GPS buoys used by the French PS fleet on logs and dFADs, in combination with logbook and observer data, to quantify the number of French GPS buoys, as well as the portion of the entire FOB “population” that French objects represent. From this, we extrapolate to the total number of GPS-equipped FOBs by season, fishing area, fleet, and FOB type.

3.3 Material and Methods

Hereafter, the term “drifting FAD” (dFAD) will be used to describe any drifting object that has been built and deployed at sea by fishing vessels to aggregate tropical tuna. The term “log” will be used in opposition to “dFAD” to designate any floating object that is not a dFAD (Table 3.1). Though logs are generally randomly found by tropical tuna purse seiners, once found, they can be used similarly to dFADs to detect the presence of tuna schools and increase the success of fishing sets. This includes the potential attachment of a GPS buoy to a log or the deployment of a dFAD on a log to enhance its floatability. The term “Floating OBject” (FOB) will be used to refer to dFADs or logs, without specifying the nature of the floating object (Table 3.1).

When a FOB is equipped with a GPS buoy, we will refer to the object as a “GPS buoy-equipped FOB” (Table 3.1). GPS buoys can be deployed either during the deployment of a new dFAD, or as a result of a random encounter with a FOB that was not previously equipped with a GPS buoy (e.g., unaltered log) or was equipped with a GPS buoy belonging to another vessel (in which case the finding vessel may replace the GPS buoy with one of its own GPS buoys). Three main groups of purse seiners operate in the Atlantic and Indian Oceans (French, Spanish and Other), each maintaining a certain number of GPS-equipped FOBs (Table 1). Here, the terms ‘French’ and ‘Spanish’ include respectively all the flags of convenience of European fishing companies of each member State, i.e. Dutch Antillas, Panama, Belize, Cape Verde, Saint Vincent, Seychelles, Malta, and Mauritius. ‘Other’ includes purse seiners from Japan, South Korea, Iran, and Thailand in the Indian Ocean and from Ghana, Guinea Conakry and Ivory Coast in the Atlantic Ocean. In this paper, we quantify the number and type of GPS-equipped FOBs maintained by each group of fleet purse seiners over time and space while the numbers of Free-Floating FOBs (i.e. unequipped with buoys) will not be estimated here.

Table 3.1: Typology of Floating OBjects (FOBs) used by tropical tuna purse seine fleets depending on the origin of the object (log or dFAD) and of the presence of a GPS buoy. Data were only available for GPS buoy-equipped FOBs. Numbers of Free-Floating FOBs (in grey) were therefore not estimated in this study. dFAD = man-made drifting Floating OBject; LOG = any floating object that is not a dFAD.

	Free FOB	**GPS buoy-equipped FOB**		
FOB type		**French** + associated fleets (e.g. Mauritius)	**Spanish** + associated fleets (e.g. Seychelles)	**Other:** Asian PS fleets + other fishing gears (BB)
Natural log e.g. marine mammal, tree **or Artificial log** e.g. debris of human activities	Free-LOG	LOG_{fr}	LOG_{sp}	LOG_{oth}
dFAD e.g. bamboo or metallic raft	Free-FAD	FAD_{fr}	FAD_{sp}	FAD_{oth}
FOBs = dFADs + logs	Free-FOB	FOB_{fr}	FOB_{sp}	FOB_{oth}

3.3.1 Data sources

Three major data sources were used: French logbooks, French and Spanish onboard observer data, and GPS positions for French GPS-buoys attached to FOBs. French logbook data provided positions for the 17,914 FOB fishing sets carried out by French purse seiners over the period 2007-2013. Similar data were not available for this study for Spanish and other non-French purse seiners. For a subset of French and Spanish PS fishing trips, onboard observers were present and collected additional, detailed information on FOB activities, including position, the type of FOB (dFAD or log), the type of activity on the FOB (deployment, visit, fishing or retrieval) and the type of activity on the attached GPS buoy (deployment, retrieval or visit). In addition, observers have the possibility to provide more detailed information on FOB activities, such as the fleet (French, Spanish or Oother) of the vessel owning the GPS buoy. This information was available for 66.7% of the 20,800 distinct activities on GPS buoy-equipped FOBs noted by observers. Observer data were available for ~5-10% of French and Spanish PS fishing trips (Appendix B1, Tables B1 and B2) and covered a wide zone of the Eastern Atlantic Ocean and Western Indian Ocean (Figure 3.3). During 2010-2013, problems of piracy off Somalia in the Indian Ocean (Chassot et al., 2010) prevented the boarding of observers on Spanish vessels for security reasons and restricted observers on French purse seiners to safer fishing grounds, mainly such as the Mozambique Channel.

Finally, the positions of FOBs equipped with French GPS buoys were available for the Atlantic and Indian oceans. A detailed description of the data coverage and the methodology used to filter and process the data can be found in Maufroy et al. (2015 - chapter 1) and in Appendix B1. FOB position data used for this study included more than 2,490,000 drifting positions from 14,415 distinct GPS buoys covering the period January 2007 to December 2013. GPS buoy trajectories varied in time length from less than a day to more than a year, with periodicity of position data also varying, but typically being either hourly or daily. French GPS buoy positions covered the entire Atlantic and Indian oceans, extending beyond typical tropical tuna fishing grounds (Figure 3.3). However, as observer data were restricted to fishing grounds, French GPS buoy data were only used within these areas.

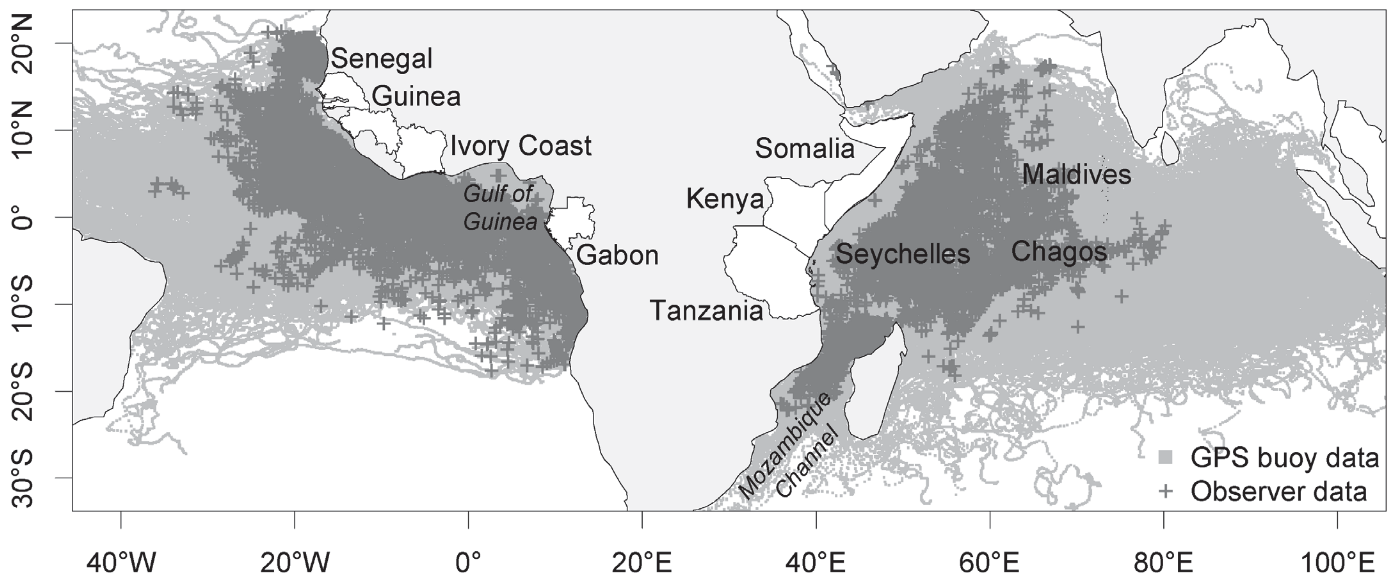


Figure 3.3: French GPS buoy data (pale grey) and observer data collected onboard French and Spanish vessels from 2007 to 2013 (dark grey)

3.3.2 Seasonal trends in dFAD and GPS buoy deployment strategy

French GPS buoy positions data were used to assess seasonal trends in FOB use. We assumed that seasonality in use of GPS buoys by French purse seiners is also representative of other PS fleets, i.e., that French purse seiners deploy GPS buoys in the same areas and with the same seasonality as other PS fleets, though not necessarily in equal numbers or with the same relative spatial distribution. This assumption is supported by similar overall spatial extents of FOB fishing sets for the three types of fleet, though Spanish fishing grounds are somewhat more extensive than French ones (e.g. off Mauritania in the Atlantic Ocean or in the north of Somalia in the Indian Ocean; Delgado de Molina et al. 2014; Chassot et al. 2015).

Seasonal trends in GPS buoy deployment were assessed based on the starting positions of at sea trajectories of French GPS buoys. A deployment season was defined as a group of successive months with similar relative spatial patterns of GPS buoy deployments (i.e., density maps of positions where GPS buoys entered the water). Only one of the three French fishing companies provided data for each month of the entire period 2007-2013. To avoid bias, one degree gridded mean monthly density maps of deployments were built using only data from this fishing company. Two-fold Pearson correlations between these monthly maps were used in a cluster analysis to determine GPS buoy deployment seasons. Calculations were carried out using the cor and hclust (with Ward clustering) functions in R (Murtagh and Legendre, 2014; R Core Team, 2015). A similar approach was used on densities of FOB fishing sets derived from French logbook data over 2007-2013 to define FOB fishing seasonality. The correlation between FOB deployment and FOB fishing was measured using the Pearson correlation coefficient, at the scale of the year and at the scale of the season. Autocorrelograms were calculated on the basis of one degree gridded maps of both FOB deployment and FOB fishing using R package “RGeostats” (Renard et al., 2016). Effective sample size accounting for spatial autocorrelation structures (Clifford and Richardson, 1985) was calculated and used to test the significance of the correlation between FOB deployment and FOB fishing (Dale and Fortin, 2009) under the null hypothesis of null correlation (α = 5%). Finally, mean seasonal speed vectors of GPS buoys were represented at the scale of 5 degrees (Appendix B2).

3.3.3 From French GPS buoys to a total number of monitored dFADs

French GPS buoy tracking data only provide information on the number of buoys at sea deployed by French purse seiners (FOB_{fr}) and their location (cell *j*). Therefore, the total number of FOBs can only be calculated from French data if we also know the proportion of all FOBs that are French in each space-time stratum. Observer data from random FOB encounters within fishing grounds provide information on the relative proportion of French ($p_{fr,j}$), Spanish ($p_{sp,j}$) and Other ($p_{oth,j}$) GPS buoys (these proportions satisfying the condition $p_{fr,j} + p_{sp,j} + p_{oth,j} = 1$ in cell *j*) through the flag of the buoy reported by observers, and on the proportion of GPS buoy-equipped FOBs from each fleet that are dFADs, as opposed to logs($\alpha_{fr,j}$, $\alpha_{sp,j}$, $\alpha_{oth,j}$). GPS buoy positions data and observer data were combined by way of a raising procedure accounting for spatio-temporal strata and differences between PS fleets (i.e. in the relative proportions of dFADs and logs used by each fleet) to estimate the total number of GPS buoy-equipped dFADs (FAD) and GPS buoy-equipped FOBs (FOB) in use in the Atlantic and Indian Oceans during 2007-2013. Even though encounter rates of FOBs and detail of recorded information varied as a function of vessel and observer, respectively, there is no reason to suspect that this variability was biased with respect to the different FOB types (fleets and logs vs. dFADs). As only relative observation rates of the different FOB types were used in our analyses, they are, therefore, insensitive to this variability in absolute rates of FOB encounter and fleet/type identification.

French GPS buoy tracking data were used to estimate the number of French buoys in a given one degree cell ($FOB_{fr,j}$) at the end of each month or on an annual basis (Figure 3.4, Table 3.2). French GPS buoy trajectories were first interpolated to obtain a unique position each day at 00:00 GMT. These positions were aggregated on a 1º grid, and then a density map of French GPS buoys was generated from the number of

GPS-buoys in each grid cell *j* on the last day of each month. The last day of the month was used because one of the three French fishing companies deactivated some GPS buoys drifting outside fishing grounds on the first day of each month, and, therefore, using the last day of the month provided a better upper bound for the number of French buoys active within fishing grounds. For simplicity, we will refer to this as the "number of GPS buoys in a given month" even though it really corresponds to the number of active buoys at a precise moment during the month. Annual estimates of $FOB_{fr,j}$ in each 1° square were computed as the sum of all French GPS buoys having passed through the 1° cell *j* at some point during the year, with each buoy's contribution to the sum being inversely weighed by the number of cells it visited during the year (so that the total contribution of each buoy to the density map for the year is 1).

Observer data were then used to derive the relative proportions of FOBs of each PS fleet $p_{i,j}$ (*i* = French, Spanish, and Other) and their relative use of dFADs and logs ($\alpha_{i,j}$) in a given spatio-temporal stratum (Figure 3.4). Due to the relatively low coverage of French and Spanish fishing trips in observer data and to the lack of observer data for the Spanish PS fleet in the Indian Ocean since 2010, observer data were aggregated over several years so as to have sufficient data in each stratum. The proportions $p_{i,j}$ and $\alpha_{i,j}$ were computed for two distinct periods: 2007-2009 and 2010-2013. The relative proportions of GPS buoys belonging to each fleet were estimated based on observations of GPS buoy-equipped FOBs pertaining to other vessels that were randomly encountered at sea by purse seiners. For example, if 2 French, 2 Spanish and 1 Other GPS buoy-equipped FOBs (not belonging to the observing vessel) were noted by observers in a given spatio-temporal stratum, then the most likely composition of FOBs in that stratum was 2/5=40% French, 2/5=40% Spanish and 1/5=20% Other (see below for how this "most likely" estimate is translated into a probabilistic framework).

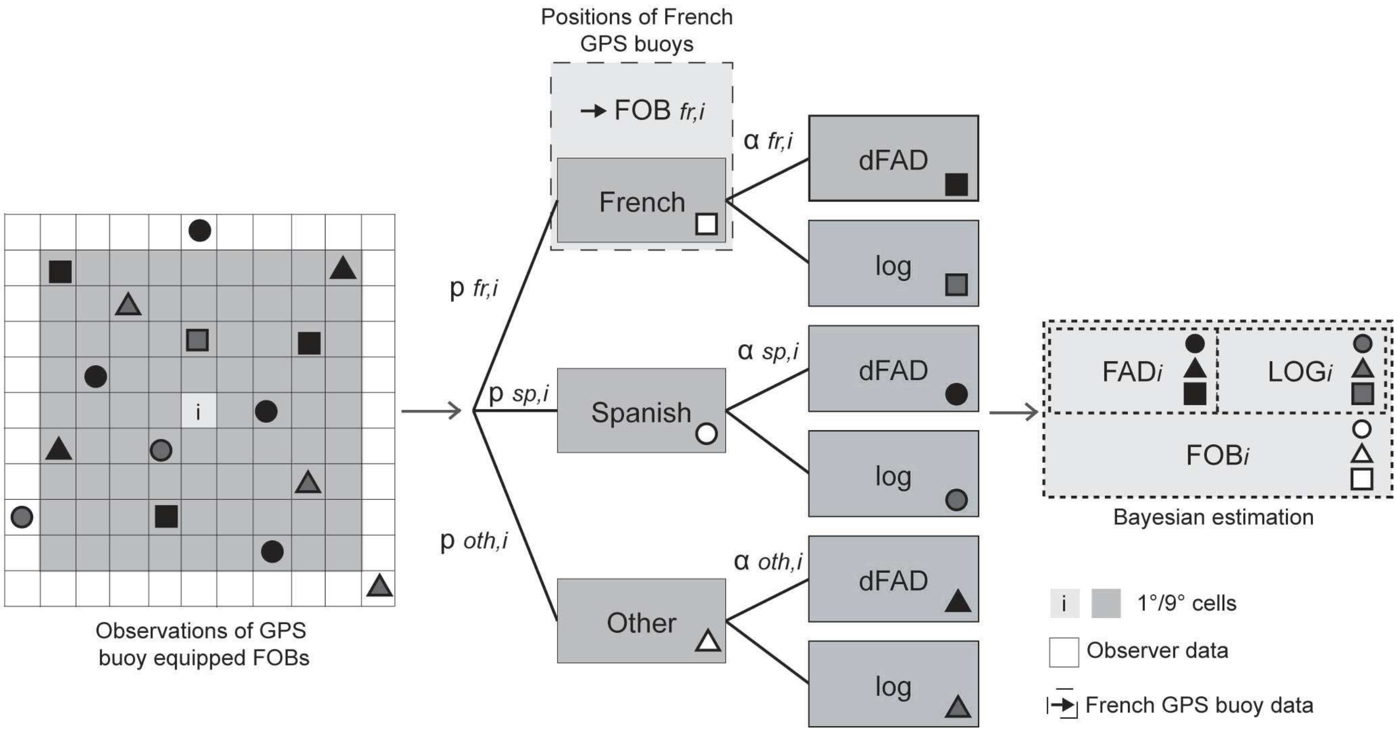


Figure 3.4: Types of GPS buoy-equipped objects and extrapolation procedure. French GPS buoy data were used to estimate the number of French GPS buoys ($FOB_{fr,i}$) in each 1x1 degree cell i (dark grey). French and Spanish observer data were used to estimate the proportions of the different types of FOBs in cells of 9x9 degrees (pale grey).

Table 3.2: data and methodology to estimate the total number of GPS buoy-equipped dFADs (FAD) and GPS buoy-equipped FOBs (FOB). *p* is the relative proportion of GPS buoys; *α* is the relative proportion of GPS buoy-equipped FOBs. *i* and j indicate fleet (i.e. French, Spanish and Other) and spatial cell, respectively.

Step	Data	Spatial stratum	Temporal stratum	Method and variables
1	French GPS buoy data	1°	1 month / 1 year	Total number of French GPS buoys $FOB_{fr,j}$
2	Observer data	9°	2007-2009 / 2010-2013	Bayesian estimation of the distribution of $p_{i,j}$ and $α_{i,j}$
3	$FOB_{fr,j}$ $p_{i,j}$ and $α_{i,j}$ distributions	whole ocean	1 month / 1 year	Raising factor to estimate *FAD* and *FOB* numbers

Similarly, the relative proportions of dFADs ($α_{i,j}$) versus logs ($1-α_{i,j}$) equipped with GPS-buoys by the French and Spanish PS fleets were derived from deployments of GPS buoys on new dFADs or FOBs found at sea. This procedure had to be modified for Other PS fleets and for the Spanish PS fleet in the Indian Ocean for the period 2010-2013 due to the absence of onboard observers. In this case, random encounters of non-owned dFADs and logs were used to calculate the proportions $α_{sp,j}$ and $α_{oth,j}$ instead of using deployments.

To avoid spatial gaps and unrealistic spatial gradients, all proportions were calculated over 9x9 degree grid cells centred on each of the 1x1 cells. Using smaller grid cells led to significantly reduced spatial coverage of observer data and high spatial variability of the proportions, while larger grid cells could mask the spatial variability in the distribution of dFADs and logs (Dagorn et al. 2013).

Uncertainty in estimates of FOBj and FADj was assessed through a Bayesian procedure to propagate uncertainty in $p_{i,j}$ and $α_{i,j}$ estimates to total GPS buoy-equipped FOBs and dFADs (see Appendix B3 for details on the procedure). For each period 2007-2009 and 2010-2013 and in each 9x9 degree cell, observations of French, Spanish and Other GPS buoys were assumed to follow a multinomial distribution. Bayesian posterior distributions for the parameters (i.e., proportions $p_{i,j}$ and $α_{i,j}$) of multinomial distributions were estimated using the Metropolis-Hastings Markov Chain Monte Carlo (MCMC) algorithm implemented in the function metrop of R package 'mcmc' (Geyer and Johnson, 2015) assuming uninformative prior distributions. Convergence of the MCMC algorithm to a stationary posterior distribution was visually evaluated through trace plots and autocorrelation diagnostics. To improve mixing, four separate MCMC chains, each with 2,500 steps, were used for parameter estimations on each spatio-temporal stratum, so as to obtain 10,000 values of proportions $p_{i,j}$ and $α_{i,j}$. Further details of the estimation procedure can be found in Appendix B3.The total number of GPS-equipped FOBs in each cell of the grid was finally calculated as follows:

$$FOB_j = \frac{FOB_{fr,j}}{p_{fr,j} \times φ} \qquad \text{(Eq. 1)}$$

where φ represents the coverage of French GPS vessels in GPS-buoy tracking data on fishing grounds (Appendix B1), $p_{fr,j}$ the relative proportion of French buoys in cell *j* derived from the Bayesian estimation procedure, and $FOB_{fr,j}$ the number of French GPS buoys in a given 1x1 degree cell *j*. Average values and confidence intervals (95%) for the total number of GPS buoys were calculated based on ensemble averaging over individual proportion estimates from the Bayesian MCMC algorithm described above.

The number of dFADs in a given cell was calculated by multiplying the total number of FOBs by the weighted average (among the different fleets) proportion of dFADs among all FOBs estimated using the Bayesian approach described above:

$$FAD_j = (\alpha_{fr,j} \times p_{fr,j} + \alpha_{sp,j} \times p_{sp,j} + \alpha_{oth,j} \times p_{oth,}) \times FOB_j \quad \text{(Eq. 2)}$$

The total number of GPS-equipped FOBs (FOB_j) and dFADs (FAD_j) were summed to obtain an estimate per ocean.

3.4 Results

3.4.1 Strategies in dFADs and GPS buoy deployment

In the Atlantic and Indian Ocean, the clustering procedure of mean monthly density maps of GPS buoy deployments over 2007-2013 produced four deployment seasons in each ocean. The different seasons were generally more distinct from each other in the Indian Ocean than in the Atlantic Ocean. The separations between groups of months in dendogram plots of clustering results occurred at heights of 0.96, 1.74 and 2.27 in the Indian and heights of 0.87, 1.22 and 1.56 in the Atlantic Ocean (Figure 3.5). Similar seasons were obtained with densities of fishing sets on FOBs, showing that activities of deployment and fishing on FOBs were correlated in time and space. Correlation between these two types of activities was generally higher in

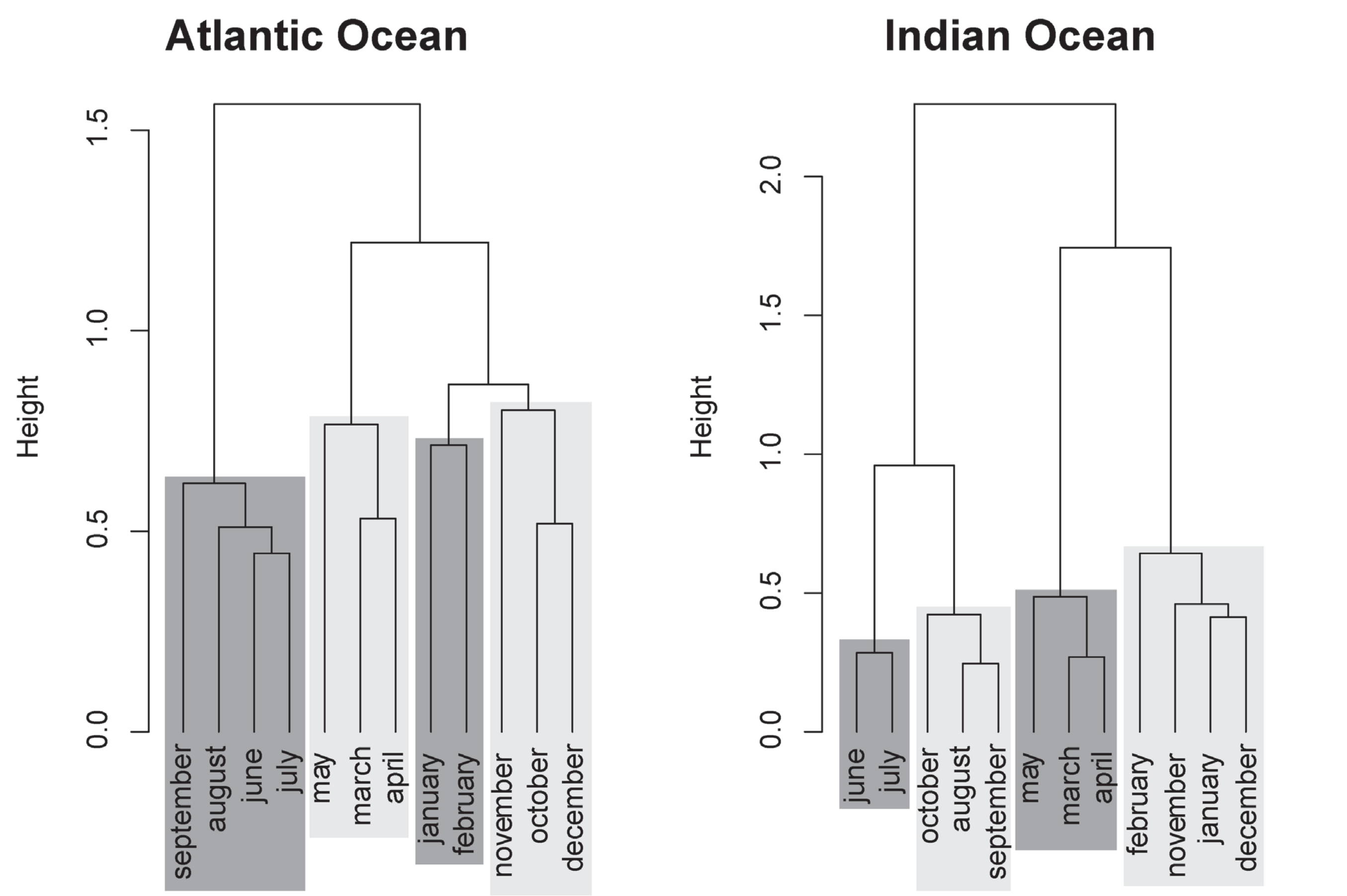


Figure 3.5: Clusters of months of GPS buoy deployments by the French PS fleet. In each ocean, four different clusters are identified, allowing the detection of four distinct seasons of GPS buoy deployments.

the Indian Ocean (Pearson correlation coefficient of 0.85 at the scale of the year, p value 2.9 e-56) than in the Atlantic Ocean (0.69, p value 2.9e-56) and varied slighlty from season to season (Appendix B2). Seasonal deployment patterns were stable whatever the resolution of the analysis (1, 2, or 5 degrees), but varied between years (Appendix B2), suggesting that a given season could occur earlier or later depending on the year.

In the Atlantic Ocean, the season June-July-August-September (JJAS) was most distinct (height=1.56). January-February (JF) and October-November-December (OND) were separated at a relatively low height of 0.83, indicating that these two seasons share common areas of GPS buoy deployments (Figure 3.6). During these two seasons, French deployments of GPS buoys on FOBs mainly occurred in 3 areas (Figure 4): Senegal (centered around 9°N, 18°W), Gulf of Guinea (1°N, 2°W) and Gabon (1°S, 7°E). The relative densities of deployments, as well as the extent of these deployments grounds varied from season to season over 2007-2013. From January to March, purse seiners progressively moved from the Gulf of Guinea (2°N,3°S/18°W,2°E) northwest to deployment grounds off Senegal (11°N,6°S/22°W,16°W). From June to September, GPS buoy deployments were relocated to the southeast and mainly occurred off Gabon (2°S,8°S/4°W,4°E). Finally, from October to December, they covered the whole Gulf of Guinea and extended westward along the Equator. Throughout the year, these deployments of GPS buoys occurred relatively close the Western Coast of Africa.

In the Indian Ocean, four seasons were detected: March-April-May (MAM), June-July (JJ), August-September-October (ASO), and November-December-January-February (NDJF). During these four seasons, GPS buoy deployments moved clockwise on four distinct deployment grounds: the Mozambique Channel area from March to May (12°S,18°S / 41°E,48°E), the West Seychelles deployment ground from June to July (7°S,1°S/46°E,53°E), the Somalia deployment ground (3°N,12°N/50°E,60°E) from August to October and finally the Southeast Seychelles deployment ground (5°S,10°S/51°E,62°E) from November to February

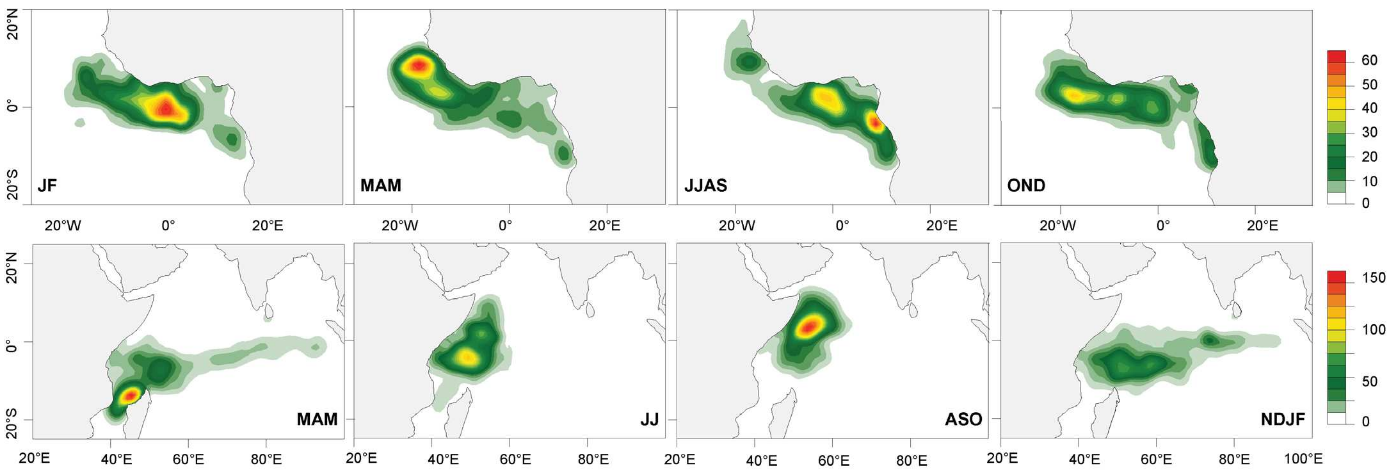


Figure 3.6: Seasonal density of GPS buoy deployments on dFADs and logs. Maps were smoothed using function kde2d of R MASS package.

Top pannel: in the Atlantic Ocean. JF: January-February; MAM: March-May; JJAS: June-September; and OND: October-December

Bottom pannel: in the Indian Ocean. MAM: March-May; JJ: June-July; ASO: August-September; and NDJF: November-February

(Figure 3.6). Though these GPS buoy deployment grounds were more distinct than those of the Atlantic Ocean, secondary zones of deployment also appeared in some seasons (e.g. North West Seychelles from March to May).

In the Atlantic and Indian Oceans, GPS buoys available to purse seiners to monitor FOBs were mainly used to track dFADs as indicated by the proportions of dFADs versus logs among GPS buoy-equipped FOBs over 2007-2009 and 2010-2013. The proportion of dFADs increased over time in both oceans, suggesting that fewer logs or more dFADs were being equipped with GPS buoys. The dFAD proportion was somewhat higher for Spanish and Other fleets than for the French fleet (0.95, 95% Confidence Iinterval [0.90;0.98] for the Spanish PS fleet and 0.88, CI [0.77; 0.95] for the French PS fleet after 2010) and in the Atlantic Ocean (0.95, CI [0.94;0.97] in the Atlantic Ocean and 0.91, CI [0.87;0.95] in the Indian Ocean after 2010).. In the Indian Ocean, there was a generally decreasing gradient of dFAD proportion among buoy-equipped FOBs from the North to the South and the East to the West of the ocean that followed main paths of oceanic currents. The Mozambique Channel area has a relatively high proportion of logs, with an average proportion of logs of 0.46 (CI [0.17;0.65]) over 2007-2009 and 0.35 (CI [0.18;0.66]) over 2010-2013. This was also the case around the Chagos Archipelago and the Maldives. In the Atlantic Ocean, 2 zones of relative higher presence of logs were observed, in the area of influence of the Niger (around 8°N-18°W) and the Congo (around 2°S-7°E) rivers. In these zones, the proportions of logs averaged 0.14 (CI [0.03;0.42]) and 0.09 (CI [0.02;0.27]¬) over 2010-2013.

3.4.2 Recent evolution of the number dFADs and GPS buoy-equipped objects

In both oceans, the number of GPS buoys per French vessel continuously increased over 2007-2013. In the Atlantic Ocean in the 2007, August was the month with the lowest use of GPS buoys with 14 GPS buoys per vessel. These numbers reached 65 GPS buoys per French purse seiner in December 2013. On average over 2007-2013, French purse seiners of the Atlantic Ocean have increased their use of GPS buoys by a factor of 5.5 (SD 2.8). In the Indian Ocean, the use of GPS buoys by the French fleet ranged from 14.2 GPS buoys in February 2007 to a maximum of 80.5 GPS buoys per vessel in September 2013. On average over 2007-2013, French purse seiners of the Indian Ocean have multiplied their use of GPS buoys by a factor of 5.8 (SD 1.2).

The strong observed increase in French use of GPS buoys is mirrored in our estimate of GPS buoy used by all fleets (Figure 3.7, Appendix B3 Table S3). In the Atlantic Ocean, it is estimated that 1,174 dFADs (CI [909;1,692]) and 1,289 GPS buoys (CI [1,001;1,852]) were in use in January 2007. In 2013, these numbers reached maximums of 8,575 dFADs (CI [5,748;14,110]) and 8,856 GPS buoys (CI [5,964;14,487]) at the end of August. On average, the monthly use of dFADs by all fleets was multiplied by 7.0 (CI [2.65;12.5]). Though the seasonality was less obvious than in the Indian Ocean, there was generally a low season in the use of dFADs by all fleets from May to August and a higher level of use during the rest of the year. Estimated numbers of dFADs were generally higher for the Spanish fleet than for all other fleets. For example, during 2013, the Spanish, French and Others PS fleets are estimated to have accounted for 74.3%, 8.3% and 17.4% of the dFADs drifting in the Atlantic Ocean.

In the Indian Ocean, October was the main month of FOB use in 2007 with 2,252 dFADs (CI [1,840;3,138]) and 2,679 GPS buoys (CI [2,165;3820]). This number increased to reach 10,307 dFADs (CI [9,083;12,444]) and 10,929 GPS-equipped FOBs (CI[9,631;13,234]) at the end of September 2013. On average, this represented an increase of a factor 4.2 (CI [1.6;8.92]) in the use of dFADs by all PS fleets. There was a stronger seasonality in the use of dFADs in the Indian Ocean than in the Atlantic Ocean. A primary peak of in the use of dFADs was generally observed from August to September, when PS fleets concentrate their activities off the coast of Somalia. During certain years, this peak began earlier in the year (e.g., June-July in 2012 and 2013) as purse seiners prepare for the Somalia season by deploying new dFADs and new GPS buoys off the coasts of Kenya and Tanzania. A secondary peak was also observed from March to May, as purse seiners dedicate most of their time to the Mozambique Channel area. Again, the Spanish PS fleet used more dFADs (87.5% in 2013) than the French fleet (10.2%) and non-European PS fleets (2.3%).

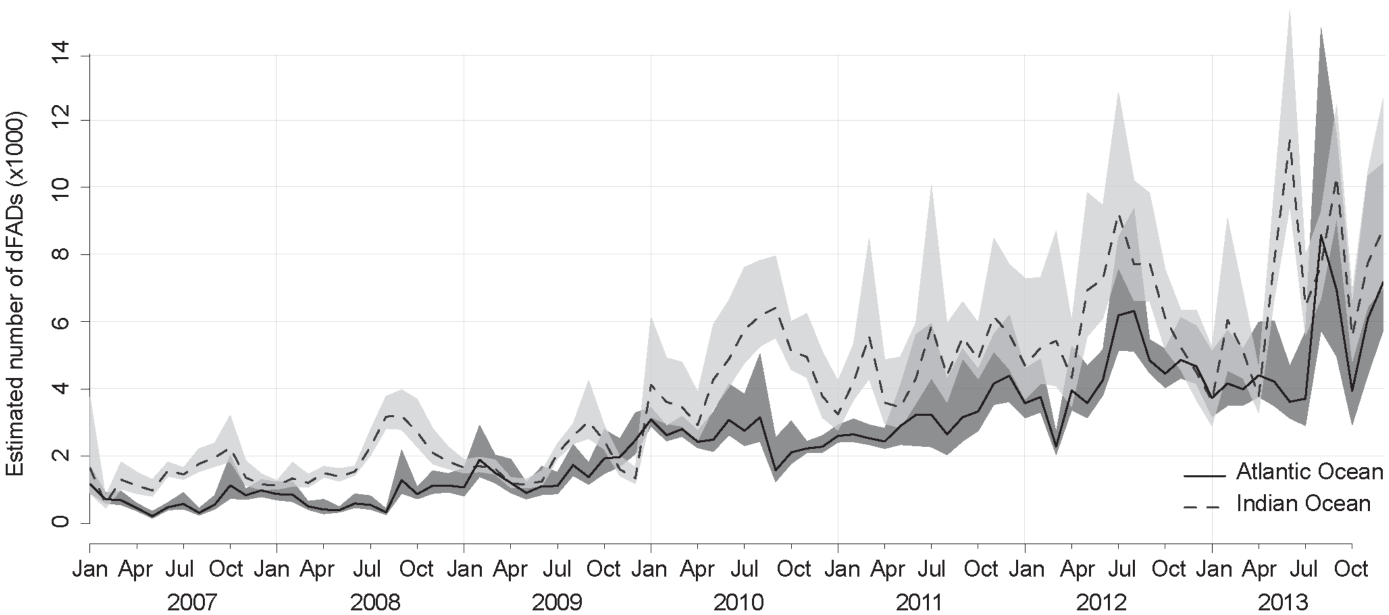


Figure 3.7: Estimation of the total number of GPS buoy-equipped dFADs in the Atlantic (solid line) and Indian (dashed line) oceans, at the end of each month (2007-2013)

3.5 Discussion

In recent years, due to growing concern regarding the state of tropical tuna stocks and pelagic ecosystems, tuna RFMOs have implemented dFAD management plans. However, due to missing exhaustive information on dFAD and GPS buoy use, it is still difficult to identify changes in FOB fisheries and to measure their magnitude. Here, for the first time, an estimate of the total number of FOBs used by all fleets, as well as the uncertainty in this estimate, has been obtained via an extrapolation based on combining information from multiple datasets. Results indicate that the number of dFADs deployed in the Atlantic and Indian Oceans increased by factors of 7.0 and 4.2, respectively, over the period 2007 to 2013. This major increase in FOB use over the last decade has been previously hypothesized (Davies et al., 2014; Fonteneau and Chassot, 2014) but not verified until now. The present study underlines the need for detailed information on FOB use of all fleets for improved evaluation of the impacts of FOB use and management of tropical tuna fisheries.

3.5.1 Strategies in dFAD and GPS buoy deployment

Seasons of GPS buoy deployment identified here are consistent with previous studies of FOB deployment and fishing (Hallier et al., 1992; Ariz et al., 1999; Ménard et al., 2000; Kaplan et al., 2014; Torres-Irineo et al., 2014). For the French fleet, deployment and fishing on FOBs were correlated in time and space, indicating that purse seiners deploy dFADs and GPS buoys where they are actively fishing. A large proportion of these deployments may occur during GPS buoy transfers (i.e. replacements of foreign GPS buoys). As compared to French purse seiners, most Spanish purse seiners however operate in collaboration with support vessels which can deploy dFADs and transfer buoys away from the purse seiner fishing grounds (Ramos et al. 2010). Preliminary information on buoy deployments available from Seychelles support vessels suggests a separation in space and time between the purse seiners and their associated vessels (Assan et al. 2015). Future estimates of dFAD use should include information from support vessels when it becomes available to complement the data used in the present study.

GPS buoy deployment seasons also allow us to understand how fishers use oceanic currents to deploy new dFADs and GPS buoys (Appendix B2). In the Atlantic Ocean, GPS buoy were generally deployed east of 20°W in the South Equatorial Current, closer to the coast than in the Indian Ocean. The strong westward currents that are active throughout the year in the Atlantic (Ariz et al., 1999; Philander, 2001) were probably avoided to reduce the risk of losing dFADs and GPS buoys (Maufroy et al., 2015). In the Indian Ocean, a similar behaviour was observed during the season NDJF with respect to the eastward South Eastern Counter Current (SECC) (Schott et al., 2009), which is capable of rapidly transporting FOBs to the east of the Indian Ocean, where they may beach on the coasts of the Maldives, Chagos or Indonesia (Maufroy et al., 2015). During the rest of the year, Indian Ocean purse seiners targeted the rich waters of the eddies of the Mozambique Channel (Sætre and Da Silva, 1984) and of the upwelling zone off Somalia (Sætre and Da Silva, 1984; Shankar et al., 2002). Lagrangian numerical simulations are currently being conducted with the Ichthyop tool to model the drift of dFADs in the Indian Ocean using ocean surface currents derived from satellite surface topography and vector winds (Lett et al. 2008). The objectives are: (i) to test the hypothesis that skippers anticipate the ocean current drifts when they deploy dFADs at sea to prepare future catch and (ii) to identify time-areas that could be closed to dFAD deployments in an overall context of purse seine fleet overcapacity and recent overfishing of the yellowfin tuna stock (IOTC 2015).

3.5.2 Estimating the use of FOBs in the Atlantic and Indian Oceans

Our estimates for the total number of dFADs are generally consistent with previous estimates of dFAD and GPS buoy use. In the Indian Ocean, Moreno et al., (2007) estimated that there were approximately 2,100 dFADs at sea in 2007 at any given moment. For 2007, our monthly estimates for the Indian Ocean ranged from 590 in February (CI [455;808]) to 2,252 in October (CI [1,840;3138]). At the annual scale, we estimated the number of dFADs and GPS buoy-equipped FOBs used to be 7,050 and 8,550, respectively, in 2009 (Appendix B3), Baske et al. (2012) estimated that there were 7,600 dFAD deployments for the same year. In the Atlantic Ocean, Ménard et al. (2000) suggested that more than 3,000 radio buoys could have been used in 1998. If this is the case, our estimate of 2,600 dFADs and 2,700 GPS buoys in 2007 is consistent with the decrease in the number of purse seiners in the Atlantic that occurred between 1998 and 2007 (Delgado de Molina et al., 2014). Furthermore, it was estimated that 9,000 dFADs were deployed in the Atlantic Ocean in 2010 (Baske et al., 2012), which is close to the 9,500 dFADs and 9,800 GPS buoys we estimated for the same year (Appendix B3). However, any comparisons between our results and other estimates are at best approximate as they often do not represent equivalent measurements. For example, the number of “dFAD deployments” estimated by Baske et al. (2012) is not precisely equivalent to our annual or monthly-instantaneous estimates of the number of active dFADs.

Though these estimates are consistent with previous knowledge, the use of observer data, covering 3% to 45% of French and Spanish fleets (Appendix B1) and the absence of observers aboard Spanish vessels in the Indian Ocean after 2010 due to piracy off Somalia (Chassot et al., 2010), limited the number of observations of GPS buoy-equipped FOBs, a major contributor to the relatively high level of variability and uncertainty in our estimates. In particular, the amount and the quality of the information available in observer data varied between observed fishing trips, either because of a lack of experience of the observer or due to few detections of FOBs by the vessel. As there was no reason to believe that some vessels are more skilled at finding dFADs from one fleet than another or log vs dFADs, this should only affect the level of uncertainty in our estimates, due to reduced number of observations. Furthermore, data limitations prevented assessment of possible inter-annual changes in the relative proportions of GPS buoys of each fleet, as well as intra-annual variability in the amount of logs introduced to the ocean due to seasonality in river discharge (Ariz et al., 1999). Finally, purse seiners of one of the French fishing companies have been remotely deactivating GPS buoys drifting too far from fishing grounds on the last day of each month since 2010. In each ocean, this produced large fluctuations of the total number of French GPS buoys between the end of a given month and the beginning of the next month. Therefore, we used French GPS buoy data at the end of each month as a reasonable proxy for the number of French buoys inside fishing grounds. However, this makes it impossible to examine daily fluctuations in FOB distributions and likely underestimates the total size of the GPS-buoy equipped FOB population inside and outside of fishing grounds.

3.5.3 Assessing the impacts of dFAD and GPS buoy use

Our results demonstrate that artificial dFADs are now the dominant form of FOB in all PS fishing areas of the Atlantic and Indian Oceans. Even in relative “dFAD-free” zones, the level of habitat modification through the use of dFADs is high and increasing in recent years. For example, in the Mozambique Channel of the Indian Ocean, the introduction of dFADs may have increased the numbers of FOBs by 110% (Dagorn et al., 2013) to 270% (our resultspresent study). Model results suggest that high densities of FOBs may lead to fragmentation of tuna schools associated with FOBs, though the density at which this fragmentation may occur is not known (Sempo et al. 2013). Furthermore, dFADs may impact the pelagic ecosystems targeted by tropical tuna fisheries via a number of other mechanisms, such as overfishing (Dagorn et al., 2013b; Fonteneau et al., 2013) ghost fishing (Filmalter et al., 2013), marine debris (Balderson and Martin 2015; Maufroy et al., 2015), disturbance to tuna spatial distributions (Hallier and Gaertner, 2008; Marsac et al., 2000) and alteration of schooling behavior (Sempo et al., 2013). Combined with bycatch, ghost-fishing and/or echo-sounder buoy data, our estimated densities of FOBs could be used to assess these potential dFAD impacts. This would represent a considerable improvement over the extensive speculation, but little concrete evidence, surrounding a number of these impacts, (e.g., the potential for an ecological trap effect ISSF 2014).

Finally, purse-seine fishing effort in the Atlantic and Indian Oceans has been modified by not only the increasing number of GPS-buoy equipped FOBs, but also the increasingly sophisticated technological means aboard tuna purse seiners (Torres-Irineo et al., 2014), the introduction of echosounder GPS buoys capable of assessing FOB-associated tuna aggregations in real time (Lopez et al., 2014), and the increasing use of support vessels (Assan et al. 2015). For a better evaluation and management of the tropical tuna PS fisheries, the collection of dFAD information through dFAD management plans should be reinforced and collaboration with fishermen would be required, as in this study. In particular, detailed information on the use of FOBs by all purse seine fleets would be necessary for a precise evaluation of the contribution of GPS buoy-equipped FOBs to overall fishing effort and the fishing capacity of tropical tuna purse seiners.

Appendix B1: Details on GPS buoy tracking data and observer data

Calculating the coverage of French GPS buoy tracking data

3 French fishing companies operated in the Atlantic and Indian Oceans over 2007-2013. Over time, the coverage of their fishing vessels increased to reach 100% on a yearly basis in 2010. Indeed, during several periods, no data was available for 2 of the 3 fishing companies. However, at a finer time scale, due to storage and exporting issue, data is missing for 2 of the 3 fishing companies for periods of a few days to a few months. During these periods, we calculated a vessel coverage as the ratio between French fishing vessels belonging to the companies having provided data and the total number of French fishing vessels.

Besides, for the last fishing company, in the Indian Ocean, only a fraction of the total number of GPS buoys was provided for 2007 and for the beginning of 2008 but the corresponding coverage was unknown. To solve this problem, fishing company 1 indicated that 100 buoys were in use per vessel in the Indian Ocean at that time. Using data available for this company over 2009-2013, we evaluated the expected number of GPS buoys for fishing company 1 as the mean ratio between buoys used each month and buoys used on a yearly basis. Combining this information with the number of purse seiners of company 1, we assumed that the coverage of this company was the ratio between provided buoys and expected buoys. Coverage of French fishing vessels and fishing company 1 GPS buoys were combined to provide a final coverage of all French GPS buoys each month of 2007-2013 (Figure B1).

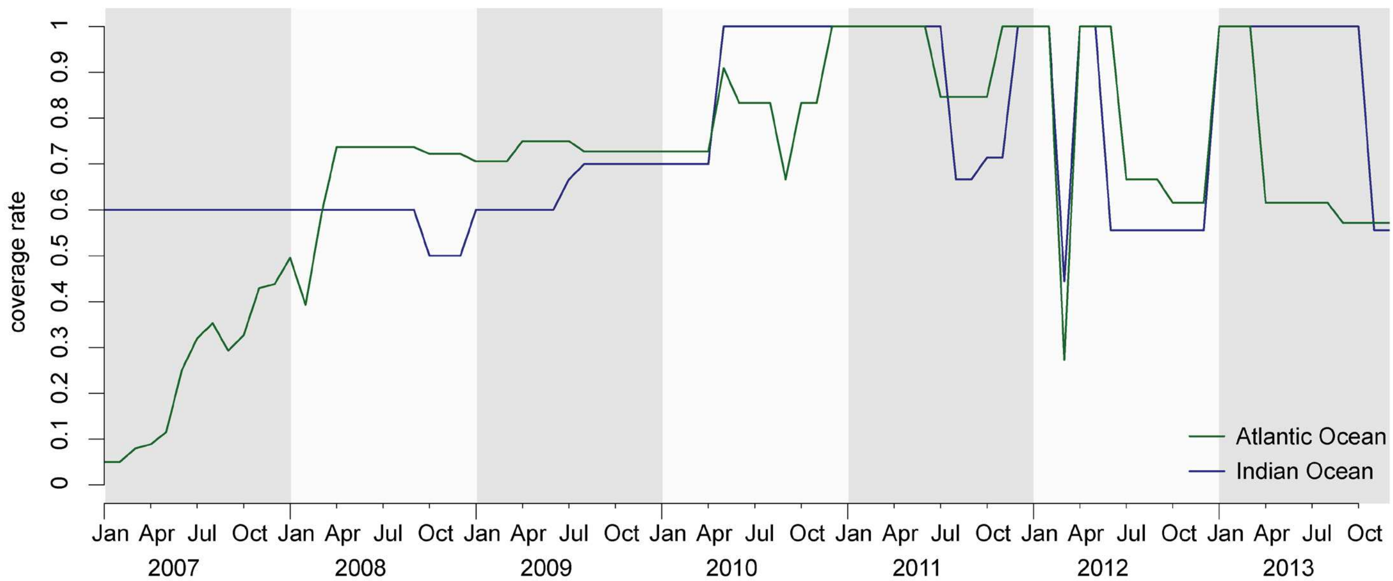


Figure B1: coverage rate of French GPS buoys tracks (coverage French vessels x coverage fishing company 1)

Coverage of French and Spanish Observer data

Observer data were collected by French and Spanish institutes over 2007-2013 (Chavance et al., 2012; Chassot et al., 2014; Delgado de Molina et al., 2014.). They covered varying fraction of fishing trips, with a fraction of fishing trips being generally larger in the Atlantic Ocean than in the Indian Ocean, primarily due piracy off Somalia (for security reasons, less observers were onboard Indian Ocean purse seiners since 2010).

Table B1: quarterly coverage (%) of French trips by onboard observers. AO: Atlantic Ocean, IO: Indian Ocean

Year	Jan-Mar AO- IO	Apr-Jun AO- IO	Jul-Sep AO- IO	Oct-Dec AO- IO
2007	10 ; 5.1	0 ; 10.3	18.2 ; 10.3	0 ; 9.8
2008	10 ; 6.4	16.7 ; 7.7	10 ; 11.6	7.7 ; 7.1
2009	7.7 ; 7.5	0 ; 6.5	4.8 ; 3	17.6 ; 0
2010	11.8 ; 3.6	13.7 ; 0	15.8 ; 0	11.1 ; 0
2011	14.3 ; 3.3	13.7 ; 20	9.1 ; 7.1	0 ; 5.3
2012	20 ; 6.9	9.5 ; 20	8.3 ; 7.4	5.6 ; 15.2
2013	44.4 ; 12.1	8.3 ; 20.7	22.9 ; 7.7	8.3 ; 14.7

Table B2: quarterly coverage (%) of Spanish trips by onboard observers in the Indian Ocean

Year	Jan-Mar	Apr-Jun	Jul-Sep	Oct-Dec
2007	0.0	9.8	15.2	14.0
2008	5.0	7.0	10.0	12.2
2009	4.8	2.9	3.0	0.0
2010	0.0	0.0	0.0	0.0
2011	0.0	0.0	0.0	0.0
2012	0.0	0.0	0.0	0.0
2013	0.0	0.0	0.0	0.0

Appendix B2: Details on GPS buoy strategies of deployment

Seasons of GPS buoy deployment

The stability of the patterns in GPS buoy deployment was explored by varying the scale of the analysis (1,2, 5 degrees), using mean monthly density maps of GPS buoy deployment for the French fleet over 2007-2013. In the Atlantic and the Indian Oceans, deployment patterns were generally stable, whatever the resolution of the analysis, except in the Atlantic Ocean at the scale of 5° were the seasons October-December and January-February were grouped into a unique season (Figures B2-B3).

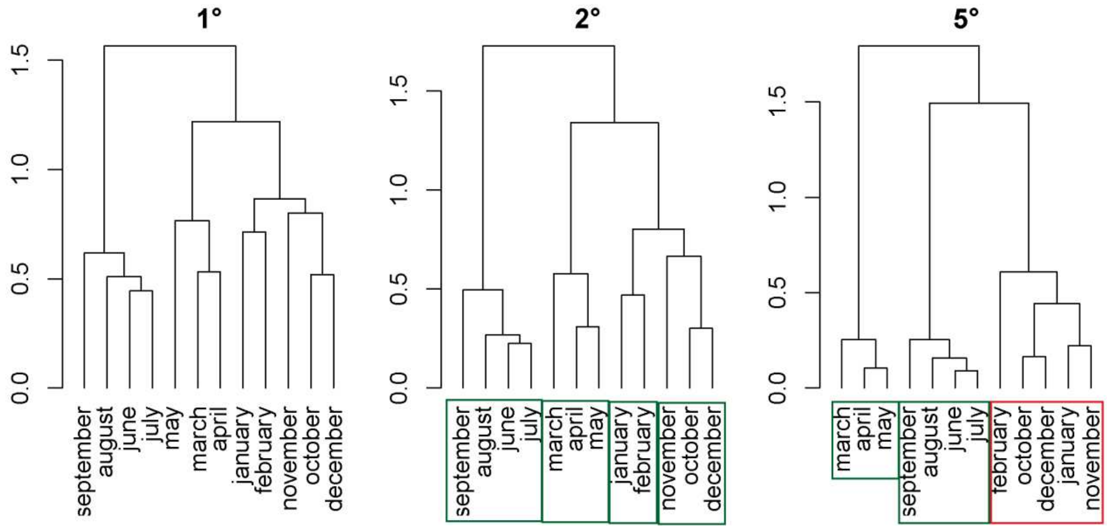


Figure B2: seasons of GPS buoy deployment in the Atlantic Ocean (2007-2013) at the scale of 1°, 2° and 5°. Green rectangles indicate that seasons are similar to those detected at the scale of 1°, red rectangles that seasons are different from those detected at the scale of 1°.

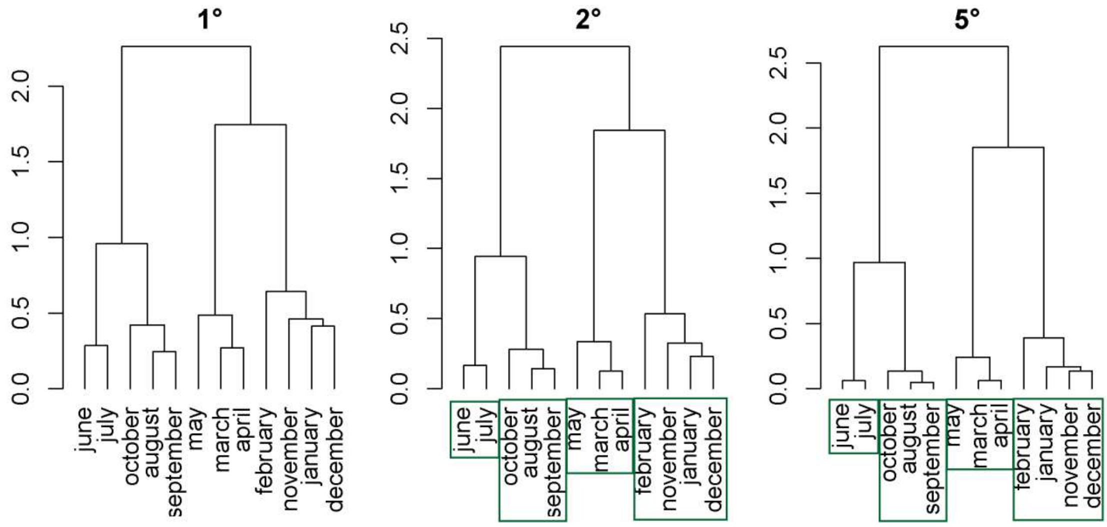


Figure B3: seasons of GPS buoy deployment in the Atlantic Ocean (2007-2013) at the scale of 1°, 2° and 5°. Green rectangles indicate that seasons are similar to those detected at the scale of 1°, red rectangles that seasons are different from those detected at the scale of 1°.

Interannual variability in the deployment was assessed by performing the cluster analysis separately for each year of 2007-2013. In the Atlantic Ocean, the seasonality was not stable from year to year. Two reasons may explain these results. First, there may be a high variability from year to year in the Atlantic Ocean. Second, the fishery occupied the same “FOB activity grounds” at different seasons, and the. The clustering method may be sensitive analysis may be sensitive to the method is not directly able to deal with to this reduced spatial extent. The season October-December was almost never detected except in 2008 and 2009 were the month of November and December were grouped together. It was also the case for the season January-February except in 2008 and 2009. At the beginning of the period, the season March-May was generally split into a season March-April (in 2007 and 2008) while a season April-May was detected in 2009 and 2012 or April-June in 2013, indicating a possible shift in the beginning of the season off Senegal. September was generally not grouped with the months June-August, though a season June-September had been detected using all years of 2007-2013, but was grouped with October from 2010 to 2013, suggesting that this month was a period of transition between different FOB fishing grounds.

In the Indian Ocean, seasons of deployment were relatively more stable from year to year than in the Atlantic Ocean. Except in 2011, all seasons March-May, June-July, August-October and November-February were detected, at least partially. In this ocean, the variability seems more related to the beginning of a given season, that can occur earlier or later depending on the year. For example, the month of May was sometimes grouped with the months June-July (in 2007 and 2008) and sometimes part of the group March-May (in 2009, 2010, 2012 and 2013).

Seasons of fishing on FOBs

Using logbook data, a FOB fishing season was defined as a group of successive months with similar relative fishing set densities in the same zones. Twofold Pearson correlations between monthly maps were used in a cluster analysis to determine FOB fishing seasons. A similar approach was used on densities of GPS buoy deployments, resulting in similar zones and seasons, showing that FOB deployment and FOB fishing activities are correlated in time and space (Figures B4-B5, Table B3).

Correlation between the two types of activities tended to be highly significant. There was generally a stronger correlation between FOB deployment and FOB fishing in the Indian Ocean than in the Atlantic Ocean. In the Atlantic Ocean, the correlation was lower during the season January-February and higher from October to December. In the Indian Ocean, the correlation was lower from June to July when purse seiners anticipate the northward drift of FOBs deployed off Tanzania and Kenya to use them later of Somalia.

Table B3: correlation between FOB deployment and fishing activities in the Atlantic Ocean (left) and in the Indian Ocean between 2007 and 2013. Correlations were calculated both at the scale of the year and at the scale of the season after accounting for spatial autocorrelation.

temporal scale	correlation
year	0.69 (p value = 2.9e-56)
Jan-Feb	0.58 (p value = 6.3e-12)
Mar-May	0.70 (p value = 1.8e-52)
Jun-Sep	0.67 (p value = 3.2e-70)
Oct - Nov	0.71 (p value = 3.3e-47)

temporal scale	correlation
year	0.85 (p value = 5.1e-72)
Mar-May	0.89 (p value = 1.0e-37)
Jun-Jul	0.72 (p value = 6.4e-39)
Aug-Oct	0.86 (p value = 1.3e-24)
Nov-Feb	0.83 (p value = 2.5e-32)

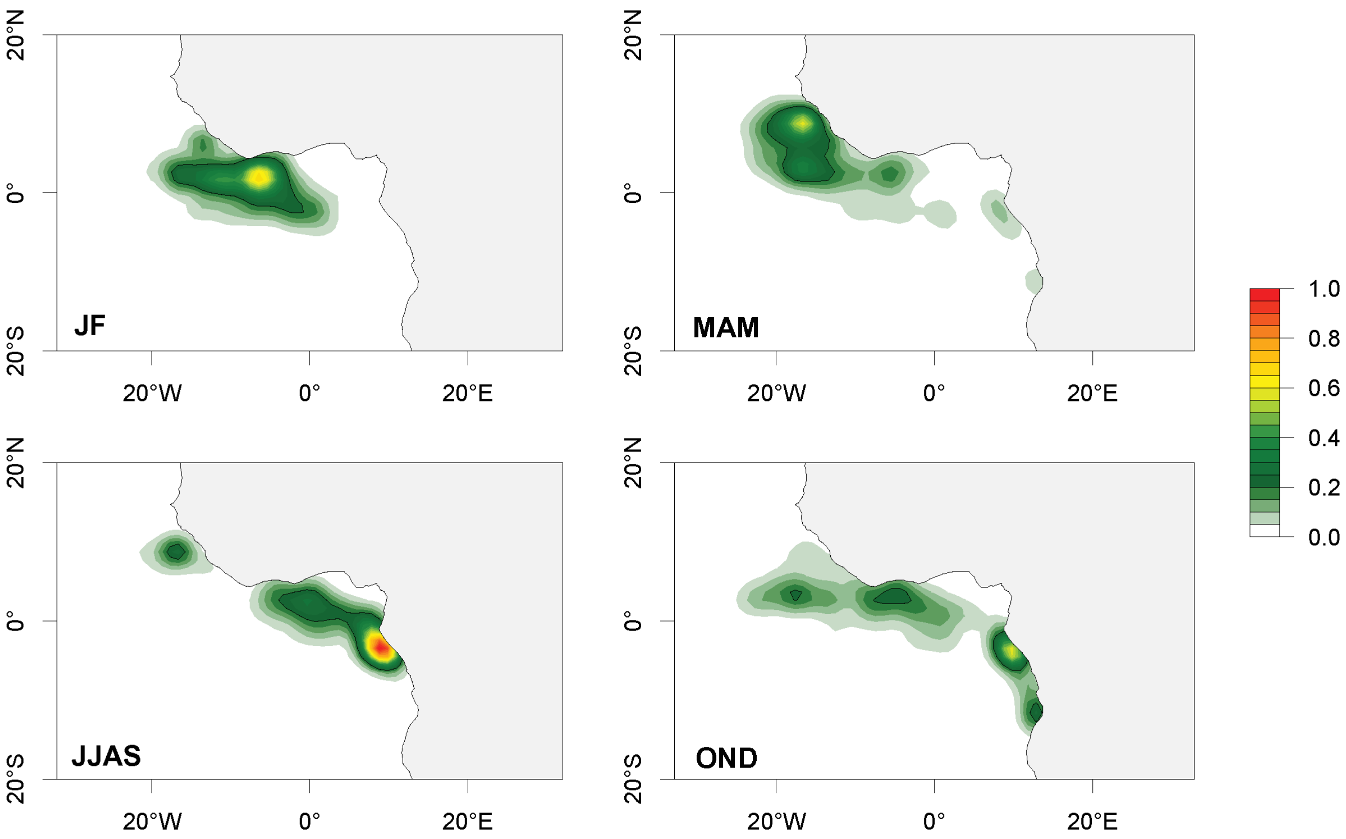


Figure B4: French seasons of fishing on dFADs and logs in the Atlantic Ocean

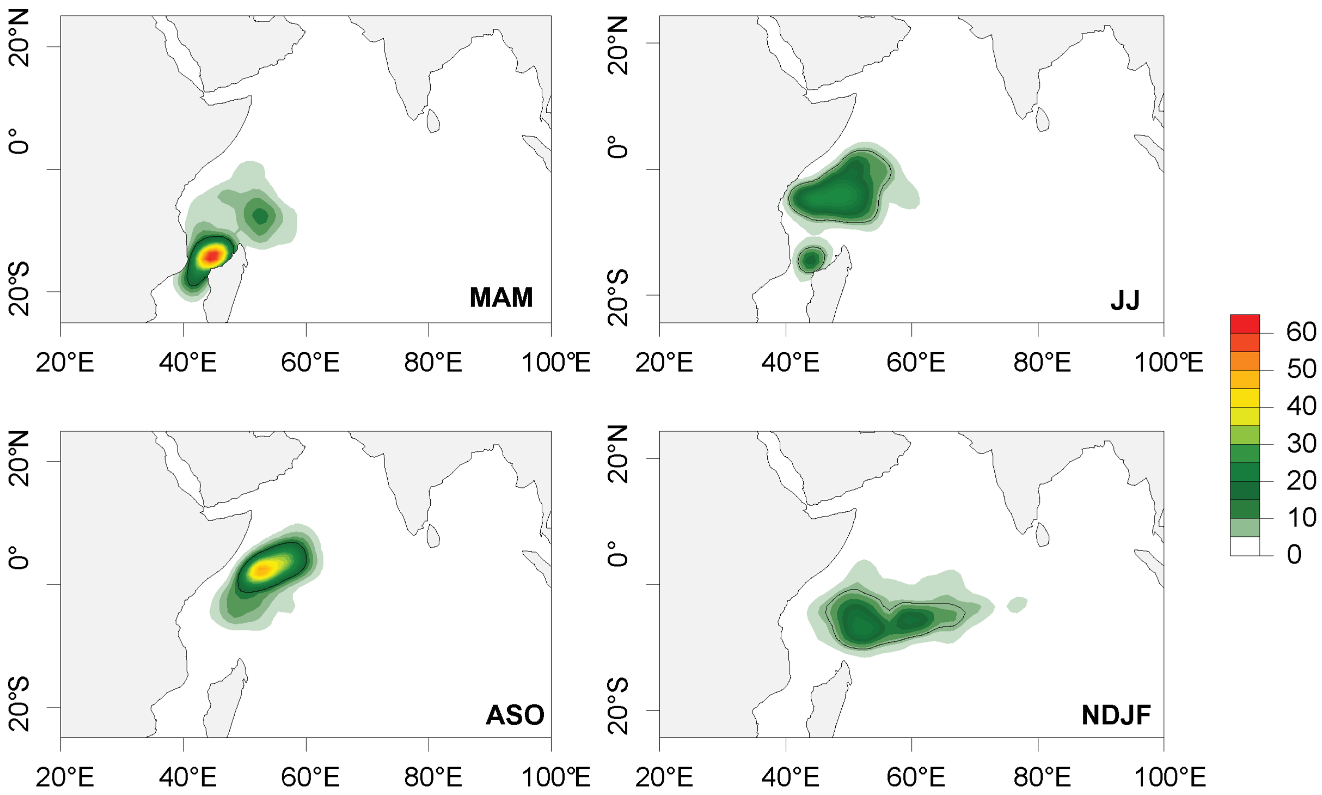


Figure B5: French seasons of fishing on dFADs and logs in the Indian Ocean

Seasonal use of currents

In the Atlantic Ocean, although seasonal variations can be observed, drift patterns are mainly dominated by two systems. Above the equator and east of 20°W, an eastward system, corresponding to the area of influence of the eastward North Equatorial Counter Current (NECC; Ariz Telleria et al., 1999; Philander, 2001), transport FOB inwards the Gulf of Guinea with a maximal mean speed of 0.31 m.s-1 from June to September. Two eastward systems, corresponding to the area of influence of the North Equatorial and the South Equatorial Currents (NEC and SEC), transport FOBs away from fishing grounds and should avoided during dFADs and GPS buoy deployment activities. These intense westwards patterns of drift reach a mean speed of 0.27 m.s-1 from March to May, when they intensify and cover a larger zone south of the Equator and east of 10°W (Figure B6).

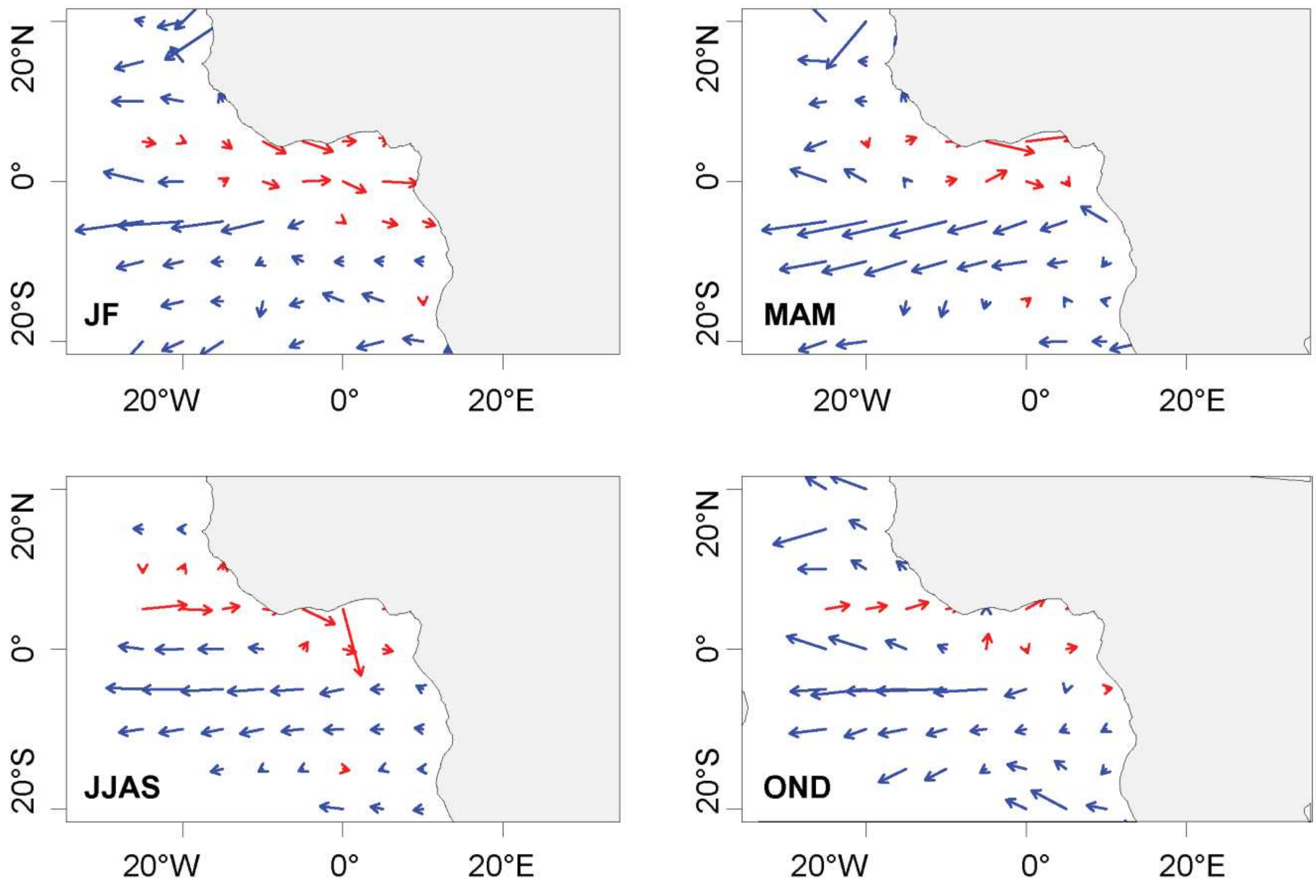


Figure B6: average speed vectors of French FOBs in the Atlantic Ocean (2007-2013)

In the Indian Ocean, during the transition from the North West Winter and South East summer monsoon circulation systems (Hallier et al., 1992), dFAD and GPS buoy deployments mainly occur in the Mozambique Channel area. At the scale of 5 degrees, two patterns of westward drift are visible transporting FOBs towards the North in an area of influence of the South Equatorial Current (SEC) and towards the South in an area of influence of the Agulhas current Eddies, that form in the North of the Mozambique Channel (Sætre and Da Silva, 1984). and are used by fishers to maintain FOBs as long as possible in productive areas where they can rapidly attract fish, are only visible at a lower scale of one degree. During the next season, fishers seem to target East African Counter (EACC) and Somali (SC) currents that become more active along the coast of Africa (Sætre and Da Silva, 1984; Shankar et al., 2002) for a northward drift of FOBs. These systems transport FOBs from the West of the Seychelles, to eastern coasts of Tanzania, Kenya and finally off Somalia where the South Gyre around 4°N and the Great Whirl around 10°N form (Schott and McCreary Jr., 2001). From

June to July and August to October, FOBs reach the cold waters of the upwelling of Somalia and maintained in this enriched area using the gyres to increase the probability of presence of fish under the objects. As the winter monsoon begins, strong eastward patterns of drift of 0.5 m.s-1 appear during the season August to September and extend during the next season. Fishers consider that this drift pattern, corresponding to the eastward South Eastern Counter Currents (SEC, Schott and McCreary Jr., 2001), can be responsible for a loss of up to 50% of their GPS buoy-equipped FOBs, as they reach the East of the Maldives-Chagos area, that is too far from fishing grounds to be visited (Figure B7).

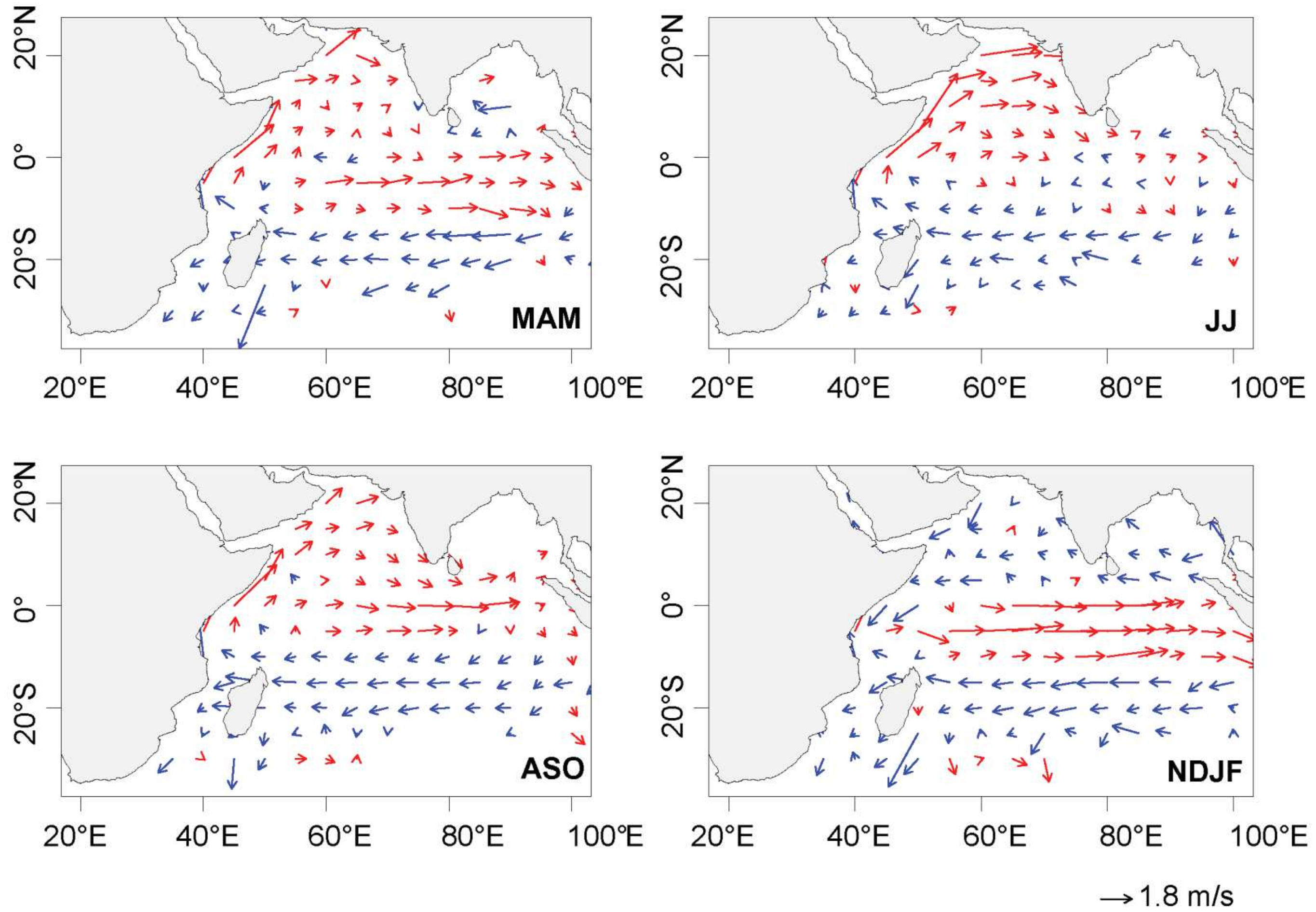


Figure B7: average speed vectors of French FOBs in the Indian Ocean (2007-2013)

Appendix B3: Details on the Bayesian estimation procedure

Proportion of dFADs α

To estimate the uncertainty in the fraction of all FOBs of French, Spanish and other purse-seine fleets that are dFADs (as opposed to logs) in a specific 9x9 degree cell, we made the assumption that the process of observing GPS buoy-equipped dFADs (as opposed to logs) of each PS fleet approximately a binomial process with probabilities αfr, αsp and αoth respectively. The probability of observing k dFADs of a given PS fleet j out of a total number n of FOBs observed for that fleet is, therefore, proportional to the binomial distribution with probability α_j (based on using Bayesian statistical inference assuming a uniform prior distribution for the proportions):

$$\Pr(\alpha_j|n,k) \propto \binom{n}{k}(\alpha_j)^k(1-\alpha_j)^{n-k} \tag{1}$$

This probability can be normalized (with respect to α_j) by integrating over all possible values of α_j, yielding the final probability density and cumulative distribution functions:

$$\Pr(\alpha_j|p_{fr},k) = \binom{n}{k}(n+1)\alpha_j{}^k(1-\alpha_j)^{n-k} \tag{2}$$

$$Q(\alpha_j|n,k) = \binom{n}{k}(n+1)\int_0^{\varphi} y^k(1-y)^{n-k}dy$$

Deployments of GPS buoys on dFADs and logs by French and Spanish purse seiners and randomly encountered Other-dFADs and Other-logs were counted in each 9x9 degree cell and for each period (2007-2009 or 2010-2013) using observer data.

Proportion of FOBs of each fleet p

To estimate the uncertainty in the fraction of all FOBs that pertain to a given PS fleet *j* in a specific 9x9 degree cell (p_j), we made the assumption that the process of observing French, Spanish and Other GPS buoy-equipped FOBs in a 9x9 zone is approximately a multinomial process with probability p_{fr}, p_{sp} and p_{oth}, respectively (assuming the total number of FOBs is considerably larger than the fraction of them recorded by observers and that FOBs of different fleets are encountered randomly). The probability of observing k_j FOBs of a given PS fleet *j* is given by the multinomial distribution:

$$\Pr(p_{fr},p_{sp},p_{oth}|k_{fr},k_{sp},k_{oth}) = \frac{\Pr(p_{fr},p_{sp},p_{oth})\prod p_i{}^{k_j}}{\iiint_0 \Pr(x_{fr},x_{sp},x_{oth})\prod x_j{}^{k_j}\,d^{m-1}x} \tag{3}$$

Where $\Pr(p_{fr},p_{sp},p_{oth})$ is the prior distribution for the proportions (noting that only two of the three proportions are independent) and the p_j, x_j and k_j must satisfy the following conditions:

$$\sum p_j = 1 \tag{4}$$

$$\sum x_j = 1$$

$$\sum k_j = n$$

The unnormalized log probability density for this distribution is:

$$k_{fr}\log(p_{fr}) + k_{sp}\log(p_{sp}) + k_{oth}\log(p_{oth}) + \log(\Pr(p_{\mathrm{fr}}, p_{\mathrm{sp}}, p_{\mathrm{oth}})) \quad (5)$$

Randomly encountered GPS buoy-equipped FOBs pertaining to the French (k_{fr}), Spanish (k_{sp}) and Other (k_{oth}) PS fleets were counted in observer data. In each 9x9 degree cell centered on each 1x1 degree cell, and for each period 2007-2009 and 2010-2013, k_{fr}, k_{sp} and k_{oth} were used to estimate the distribution of the proportion of French (p_{fr}), Spanish (p_{sp}) and Other (p_{oth}) GPS buoys FOBs with the metrop function of R package mcmc, with the unnormalized log probability density defined in Eq. 5. The «reference distance approach» of Berger et al. (2015) was used to derive the non-informative multinomial prior distribution for the proportions, yielding a bivariate Dirichlet prior: $\Pr(p_{fr},p_{sp},p_{oth})=\prod_{i=fr,sp,oth})p_i^{-2/3}$. To improve mixing in the MCMC chains, 4 different MCMC chains of 2,500 iterations each were built to obtain 10 000 values of $p_{fr,}$ p_{sp} and p_{oth}. For each of the 4 MCMC chains, metrop was run until we reached an acceptance rate of 0.25. Then, the number of batches of each iteration (i.e., the blen parameter to metrop) was adjusted to avoid autocorrelation along the MCMC chain.

Total number of dFADs and GPS buoy-equipped FOBs

Finally, daily or yearly estimates of French GPS buoys in 1x1 degree cells ($N_{b,fr}$) were combined with the 10,000 values of each proportion α_i and p_i in the appropriate 9x9 cells and for the appropriate period, 2007-2009 or 2010-2010, to obtain 10,000 values of the total number of GPS buoy-equipped FOBs (N_b) and dFADs (N_d).

Table B4: Mean estimate of the total number of GPS buoy-equipped dFADs in the Atlantic (solid line) and Indian (dashed line) oceans, per year (2007-2013) over the 10,000 iterations of the Bayesian procedure. Values of 2.5% and 97.5% quantiles of the estimated distribution of FAD and FOB are presented in square brackets.

	Atlantic Ocean		Indian Ocean	
Year	**FAD**	**FOB**	**FAD**	**FOB**
2007	2,962 [2,595;3,630]	3,296 [2,899;3,630]	7,727 [6961;9,547]	9,325 [8,360;9,547]
2008	3,763 [3,248;4,716]	4,185 [3,629;4,716]	9,323 [8,632;10,492]	11,479 [10,656;10,492]
2009	7,339 [6,344;9,492]	8,131 [7,070;9,492]	8,220 [7,739;8,958]	10,222 [9,658;8,958]
2010	8,977 [8,493;9,821]	9,419 [8,910;9,821]	19,949 [17,553;24,857]	21,658 [19,097;24,857]
2011	11,600 [10,549;13,876]	12,214 [11,120;13,876]	21,025 [18,426;26,196]	22,858 [20,094;26,196]
2012	15,138 [14,146;17,123]	15,922 [14,872;17123]	28,545 [25,193;35,203]	30,753 [27,212;35,203]
2013	17,763 [15,465;22,754]	18,449 [16,097;22,754]	31,978 [28,450;38,549]	34,659 [30,892;38,549]

CHAPTER 3:

Contribution of support vessels and Floating OBjects to the increasing efficiency of tropical tuna purse seiners in the Atlantic and Indian Oceans

4.1 Objectives of the chapter

Traditional measures of fishing effort such as days at sea or fishing time are inappropriate for purse seiners using a combination of activities on FSC or randomly encountered FOBs (random search) and GPS buoy monitored FOBs ("directed" search, Figure 4.1). Measuring the fishing effort of tropical tuna purse seiners therefore requires a specific methodology that would explicitly take into account the use of FOBs. GPS buoy data were not available for the Spanish purse seine fleet and were anonymised for the French purse seine fleet (i.e. the name of the vessel owning the buoy was not available). This information and the methodology developed in chapter 1 could therefore not be used to measure the fishing effort or the fishing efficiency of European Union purse seiners.

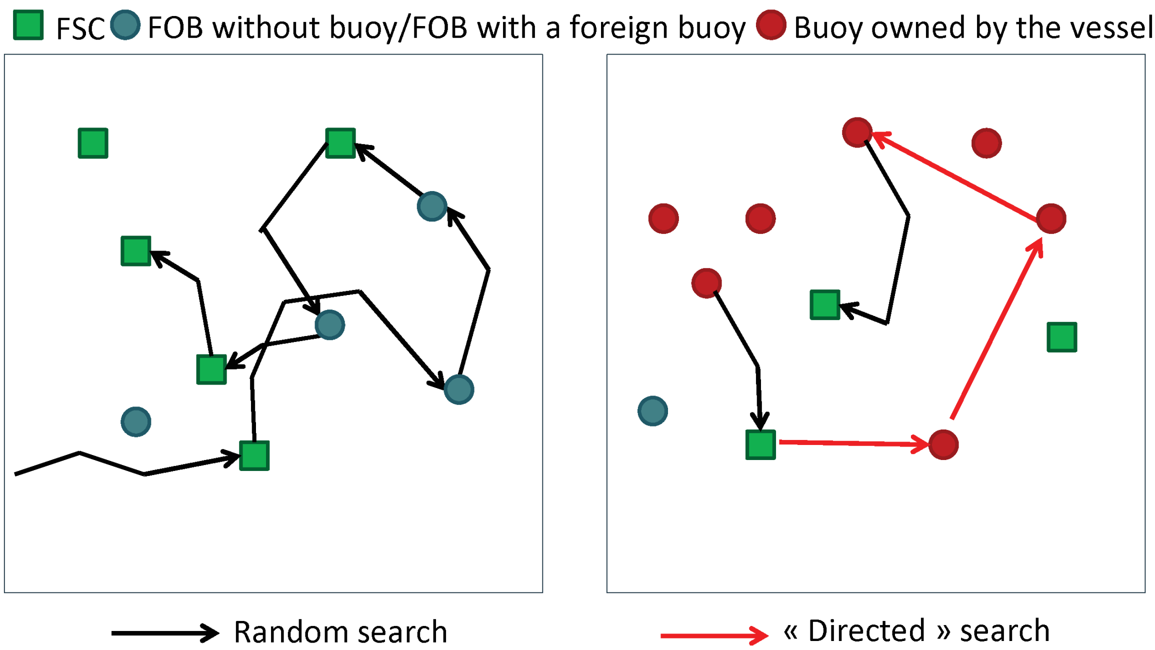


Figure 4.1: searching activities on FSC and FOBs (adapted from Fonteneau 1999)

Our initial objective was then to separate the time dedicated to FSC from the time dedicated to FOBs using Vessel Monitoring System (VMS) data, in order two build separate indices of fishing effort for the two types of school. Since 2006, the VMS position of French purse seiners is routinely transmitted every hour. The primary objective of VMS is to monitor the position of purse seiners to ensure they do not fish in forbidden areas. However, such data can be used by scientists for other purposes, such as the detection of fishing sets (Bez et al., 2011). Using similar methods to those presented in chapter 1, our objective was to:

(i) combine VMS trajectory data and logbook or observer data to separate FSC and FOB sections on a subset of purse seiners trajectories

(ii) calculate the speed, heading change, sinuosity, etc on each FSC and FOB section of trajectory of this training dataset

(iii) use this training dataset in a classification procedure and apply the full model to all VMS trajectories

(iv) build an index of fishing effort per type of school that would be based on the surface explored during FSC and FOB activities

The initial exploration of the training dataset built with logbook data indicated that there were only few differences between FSC and FOB sections of trajectories in terms of speed, sinuosity and explored surface.

This suggested that a simple separation between FSC and FOB sections was inappropriate. In reality, 3 types of behaviour may exist . Purse seiners may search for FSC (random search) or owned FOBs (“directed” search). As logbook data did not allow separating could not be used to make the separation between these 3 types of behaviour, observer data was were explored, as it would in theory allow to make such a separation to provide information on the fishing tactics of the skipper for a subset of the VMS dataset. However, due to missing information , this other source of information did not allow to fully separate activities on owned FOBs from activities on foreign FOBs.

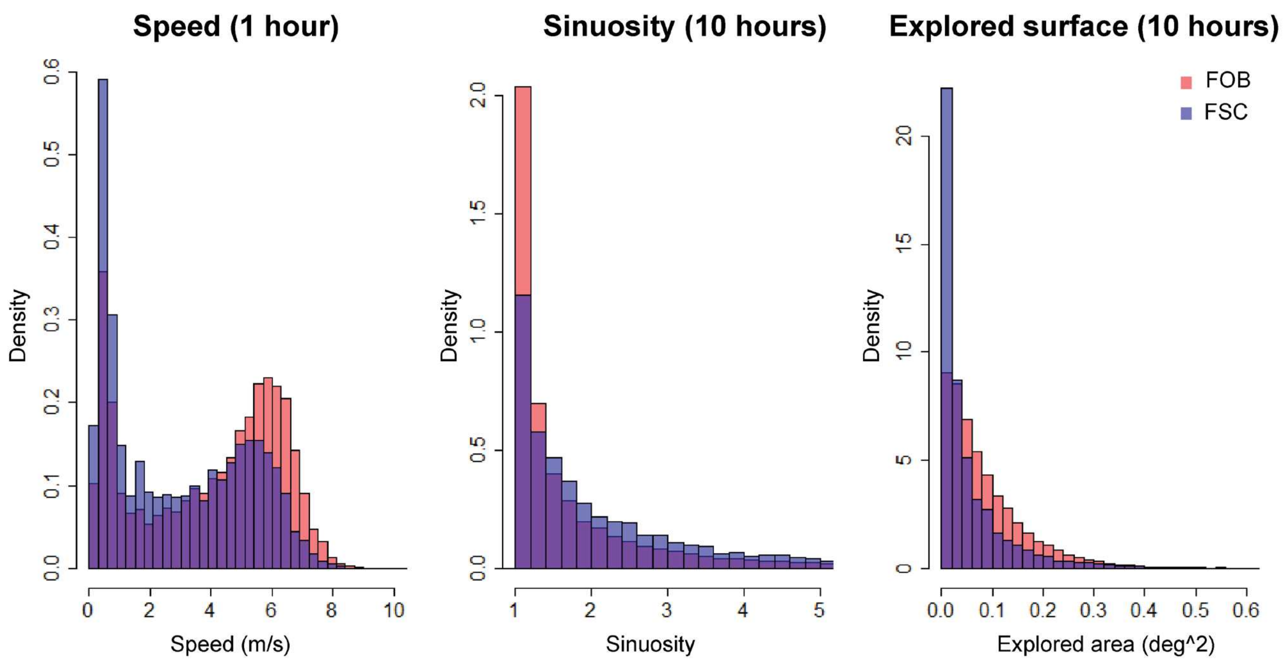


Figure 4.2: speed, sinuosity and explored surface on FSC (blue) and on FOBs (red) in the Atlantic and Indian Oceans (French purse seiners, 2006-2013)

As it was impossible to build an appropriate training dataset using the available logbook and observer data, the idea of separating FSC and FOB sections of trajectories of purse seiners was abandoned. However, logbook data could still be used to measure changes in the efficiency of purse seiners, in relation to their changes of strategies with FOBs and FSC. This was much needed as FOBs contribute to increasing the fishing power of tropical tuna purse seiners (Le Gall, 2000a). Because of the lack of information on the use of FOBs and on the contribution of support vessels, the contribution of FOB strategies is rarely measured and taken into account by tuna RFMOs. Instead, they primarily rely on catch and effort data from longliners for the assessment of yellowfin and bigeye stocks while abundance indices derived from baitboat commercial catch rates are used for skipjack. Since the 1990s, it has been generally assumed that there is a yearly increase of 2% to 3% of the fishing power of purse seiners (Fonteneau et al., 1999; Gascuel et al., 1993). It is more than likely that after more than 20 years, this assumption has become incorrect.

In chapter 3, we therefore use French and Spanish logbook data to measure changes in the efficiency of European Union tropical tuna purse seiners over 2003-2014 in the Atlantic and Indian Oceans. Information on vessel characteristics (size, fleet), use of support vessels and strategies of purse seiners with FOBs and FSC are used to build indices of fishing efficiency for the purse seine fishery in the two oceans.

4.2 Introduction

Over the past half-century, worldwide fishing effort has increased many fold as catch per unit effort (CPUE) has gone down (Pauly et al., 2002; Watson et al., 2013). Issues of excess fishing effort and fishing capacity have been raised for many fisheries worldwide, including fisheries on the high seas where these problems remain difficult to monitor and address (Greboval and Munro, 1999; Joseph, 2003). Though part of fishing effort and capacity increase is due to an increase in the number of fishing vessels, changes in fishing efficiency due to technological improvements or changes in fishing strategy are also an important component of the increase in global fishing effort and resulting fishing mortality (Marchal et al., 2007; Engelhard, 2009; Watson et al., 2013). Not accounting for changes in efficiency in fishing effort can lead to hyperstability or hyperdepletion in CPUE estimates and misleading stock assessments (Hilborn and Walters, 1992; Walters, 2003). It is, therefore, extremely important to track changes in fishing efficiency and standardize nominal fishing effort indices to account for these changes (Maunder and Punt, 2004).

Purse-seine tropical tuna fisheries have experienced significant technological and strategic changes over the last three decades which resulted in increased overall fishing pressure on tuna stocks (Gaertner and Pallares, 2002; Torres-Irineo et al., 2014; Tidd et al., 2016). In all oceans, vessel characteristics and attributes, fishing gears, and equipment for school detection and aggregation have steadily improved over time (Itano, 2002; Torres-Irineo et al., 2014). In particular, fishing on Floating OBjects (FOBs), either natural (logs) or purpose-built (drifting Fish Aggregating Devices, dFADs), has dramatically developed since the 1990s (Fonteneau et al., 2013) and technological means for FOB fishing have improved over time. From the late 1990s, satellite-transmitting GPS systems have complemented and then fully replaced radar positioning of FOBs at sea to improve location accuracy (Chassot et al., 2014; Lopez et al., 2014). Most GPS buoys now include echo-sounders to remotely monitor in real time the amount of biomass aggregated under the FOB, potentially significantly reducing wasted fishing effort associated with visiting FOBs with little aggregated tuna biomass (Dagorn et al., 2013; Lopez et al., 2014). Furthermore, collaboration with non-fishing support vessels, whose objectives are to detect tuna schools and deploy, monitor and maintain a network of GPS buoy-equipped FOBs (Ramos et al., 2010), allows purse-seiners to gain the benefits of using FOBs before they even leave port (Morón et al., 2001).

The massive and increasing use of FOBs by purse seiners since the 1990s, as well as the technologies used for FOB fishing, have had a particularly important impact on fishing efficiency (Ariz Telleria et al., 1999; Fonteneau et al., 2000; Hallier et al., 1992). In addition to the typical impacts of technological creep experienced in other modern fisheries (Torres-Irineo et al., 2014), the use of FOBs affects catchability in ways that make defining an index of fishing effort for purse seiners difficult. FOBs increase the availability of tropical tuna to purse seiners by concentrating schools (accessibility), increasing the proportion of successful sets (vulnerability) and facilitating location of tuna schools (detectability; Fonteneau et al., 2013). As FOBs reduce the time dedicated to randomly search for schools of tunas, traditional measures of fishing effort, such as days at sea or fishing time are inappropriate for tropical tuna purse seiners. In addition, tropical tuna purse seiners combine two different métiers, either targeting large yellowfin tuna in Free Swimming Schools or skipjack tuna under FOBs. As FSC and FOB activities are not separated in time and space, it is even more difficult to measure the effective fishing effort of the tropical tuna purse seine fleet.

Due to the complex nature of the fishery, the evolution of fishing capacity (Joseph, 2003; Reid et al., 2005; Morón, 2007) and fishing efficiency of tuna purse seine fleets remain poorly monitored. Quantifying changes in fishing efficiency of the purse seine fleet remains a challenge (Gascuel et al., 1993; Fonteneau et al., 1999) that requires constant monitoring of the many changes in fishing efficiency of individual purse seiners that have occurred over the years as a result of changes in vessel characteristics, fishing gears or fishing strategies (Le Gall, 2000; Gaertner and Pallares, 2002; Torres-Irineo et al., 2014). This task is further complicated by the fact that most changes in fishing efficiency have not historically been monitored and associated with a specific purse seine vessel, such as the use of FOBs or the collaboration of purse seiners with support vessels.

Here, we address these challenges by estimating changes in fishing efficiency associated with specific technological or fishing strategy changes in the tropical tuna purse-seine fisheries of the Indian and Atlantic Oceans. Using detailed temporal data on catch, number of fishing sets and travelled distance, as well as characteristics of the purse-seiners and their collaboration with support vessels, we (i) measure the intensity of changes in the relative use of FOBs and FSC, in relation to vessel characteristics and to the use of support vessels, (ii) analyze individual differences in fishing efficiency related to vessel characteristics, the use of support vessels and changes in strategies of FOB use, and (ii) identify key components of fishing efficiency in order to derive an index of fishing efficiency for tropical tuna purse seine fleets.

4.3. Material and methods

4.3.1 Definitions: strategies and efficiency of tropical tuna purse seiners

One aspect of fishing strategies that may be particularly important, but has not been extensively examined in the past, is the use of FOBs. Fishing strategies were defined here as the relative contribution of FOBs and FSC activities on the medium-term (Torres-Irineo et al., 2014). Changes in fishing strategies were measured with the proportion of fishing sets on FOBs per month (denoted P).

Table 4.1: different measures of fishing efficiency of tropical tuna purse seiners

Efficiency measure	Designation	Meaning
Catch / Fishing day	CPUE1	Ability to maximize the catch over a certain period of time
Catch / Fishing set	CPUE2	Ability to maximize the catch per fishing set
Catch / Travelled distance (km)	CPUE3	Ability to choose the optimal area for search activities
Sets / FIshing day	SPUE	Ability to detect concentrations of tuna
Distance / Fishing day	DPUE	Ability to cover a large area during search activities / to leave zones without fish rapidly

Fishing efficiency (denoted E) was measured with five different statistics (Table 4.1). We assumed that the main objective of fishing activities is to maximize catches, whilst minimizing the time at sea (measured with CPUE1), the number of fishing sets (CPUE2), and fuel consumption (using travelled distance as a proxy, CPUE3). Fishing efficiency also relates to the size of fishing sets (CPUE2), the frequency of fishing sets (to avoid long periods without fishing, SPUE) and travelled distance (to increase the size of search areas, DPUE). In order to quantify the importance of each of these different tradeoffs, we calculated a set of per unit effort indices, dividing catch, the number of fishing sets or distance traveled by an indicator of the quantity to be minimized (e.g., time at sea; see Table 4.1 for details).

4.3.2. Data sources

4.3.2.1. Vessel characteristics

Vessel length (m), carrying capacity (m3), engine power (HP) and initial year of activity were available for 112 different French and Spanish purse seiners that were active in the Atlantic and Indian Oceans at least one month during 2003-2014. Due to collinearity among these variables (larger vessels were generally more recent and had higher carrying capacity and engine power), vessel length and fleet were combined to build a variable "vessel characteristics" (denoted C). Four distinct categories of vessel size were considered (41.4-58 m, 59-72 m, 73-94 m, 95-116.2 m) and separated between French and Spanish fleets (e.g. French 41.4-58 m vs Spanish 41.4-58 m). An additional category was added for one of the French fishing companies of the Indian Ocean know to have a specific FSC strategy related to their freezing method targeting the market of large yellowfin tuna (category "73-94 m + FSC").

4.3.2.2. Use of support vessels

The link between purse seiners and support vessels of the Indian Ocean during 2003-2014 was established through Seychelles fishing licences and individual logbooks of support vessels under the Seychelles flag. A factor variable "support time" was built, with 4 categories of purse seiners: 0, if the purse seiner did not have a support vessel; 1/3 if the purse seiner shared the support vessel with 2 other purse seiners; 1/2 if the purse seiner shared the support vessel with another purse seiner; and 1 if the purse seiner had its own support vessel. This information was not available in the Atlantic Ocean.

4.3.2.3 Catch, fishing sets and distance data

Logbook data were available for the French and the Spanish purse seine fleets from 2003 to 2014 in the Atlantic and the Indian Oceans. These data were aggregated by month, approximately corresponding to the average duration of a fishing trip, so as to carry the analyses at the scale of fishing strategies. Spatial information could not be used at this scale, as purse seiners travel long distances during their fishing trips. However, as due to the monsoon phenomenon the purse seine fleet is highly seasonal in the Indian Ocean (Stéquert and Marsac, 1989; Kaplan et al., 2014), information on the month indirectly takes into account the effect of the zone on the efficiency of purse seiners. In the Atlantic Ocean, the seasonality of fishing activities is less obvious (Ariz Telleria et al., 1999) but the interest of using the variable month was tested during model selection procedures.

For consistency reasons, only vessels that spent at least 20 days at sea during the month and 100 days at sea during the year were used. A vessel known to benefit from a support vessel anchored on a seamount was eliminated from the dataset of the Indian Ocean. In the Atlantic Ocean, this resulted in a dataset of 3,365 values of monthly efficiency from 45 purse seiners. In the Indian Ocean, 4,963 values of monthly efficiency from 66 different purse seiners were available from 2003 to 2014. Datasets were unbalanced as small purse seiners were progressively replaced by large purse seiners, large purse seiners were generally belonging to the Spanish fleet and only large purse seiners were assisted by a support vessel.

Table 4.2: variables used to model the strategy and the efficiency of tropical tuna purse seiners

Variable	Designation	Meaning	Availability
Year	Y	Abundance	AO + IO
Month	M	Abundance	AO + IO
Characteristics (Initial year x Fleet)	C	Technical efficiency	AO + IO
Support time	S	Technical efficiency	IO
Vessel unique identifier	V	Technical efficiency	AO + IO
Proportion of fishing sets on FOBs	P	Strategic efficiency	AO + IO

4.3.3. Factors influencing the strategy of tropical tuna purse seiners

In a first step, Generalized Linear Models (GLMs) were used to explain fishing strategy P (logit-transformed) as a function of year Y, month M, an interaction between year and month Y:M, vessel characteristics C and use of support vessels S following:

$$\text{logit}(P_i) \sim Y + M + Y{:}M + C_i + S + \varepsilon_i$$

where *i* denotes the purse seiner and the errors ε_i were modeled with a zero-one beta inflated distribution to account for overdispersion in the monthly proportions of fishing sets on FOBs (P). Models were built using R “gamlss” package (Stasinopoulos and Rigby, 2008). Results were compared among classes of vessel characteristics and support vessel use using function “glht” of R package “multcomp” with Tukey contrasts (Hothorn et al., 2015).

4.3.4. Factors influencing the efficiency of tropical tuna purse seiners

In a second step, Generalized Linear Mixed Models (GLMMs) were used to model the five dimensions of fishing efficiency following:

$$\log(E_i) \sim Y + M + Y{:}M + C + S + P + (1 \mid V) + \varepsilon i$$

where E represents CPUE1, CPUE2, CPUE3, SPUE and DPUE and vessel V is modeled as a random effect to account for the lack of independence of errors nested under the same vessel (Moulton 1986). Error terms ε_i were assumed to follow a log-Gamma distribution. GLMMs were developed using R “lme4” package (Bates et al., 2015). To account for unbalanced designs (e.g. only the larger purse seiners were assisted by support vessels), the least squares means were computed for each factor with R “lsmeans” package (Lenth et al., 2015), to represent the effects of vessel characteristics and the use of support vessels on the efficiency of purse seiners.

4.3.5. From vessel efficiency to indices of total efficiency

In a third step, fishing efficiency was decomposed in two terms: a technical efficiency TE component and a strategic efficiency SE component such that:

$$E = TE \times SE$$

Technical efficiency was calculated as the efficiency under constant abundance and vulnerability conditions (O'Neill and Leigh, 2007, Braccini et al., 2012), that is to say independently from a given month or a given year. Effect of vessel characteristics and support vessels were used to estimate individual technical efficiency of purse seiners. For purse seiner *j*, TE_j was calculated as following:

$$TE_j = \exp(C_j + S_j)$$

where C_j and S_j corresponds to the effects of vessel characteristics and use of support vessels (as derived from efficiency GLMMs, see section 4.3.3).

Strategic efficiency was calculated as the efficiency of purse seiners during year *y* when the effects of the month, vessel characteristics and support vessels were held constant:

$$\log(SE_y) = P \times \log(P_y)$$

where P corresponds to the effect of the proportion of fishing sets on FOBs on the efficiency of tropical tuna purse seiners (as derived from the efficiency GLMMs, see section 4.3.3) and P_y corresponds to the standardized proportion of fishing sets on FOBs on year y (as derived from the strategy GLM, see section 4.3.2).

The first year of the analysis, i.e. 2003, was used as the reference year. For a given year *y*, the relative index of fishing efficiency of the purse seine fleet I_y was estimated as:

$$I_y = (\bar{E}_j)_y / (\bar{E}_j)_{2003}$$

where $(\bar{E}_j)_y$ corresponds to the average standardized fishing efficiency of purse seiners active in the Atlantic or the Indian Ocean on year *y*. This methodology was applied to each of the 5 efficiency GLMMs to compare the results obtained with the different dimensions of the efficiency of tropical tuna purse seiners. In addition, the relative contribution of the technical efficiency $I_{TE,y}$ and strategic efficiency $I_{SE,y}$ to changes the index of efficiency I_y were calculated.

4.4. Results

4.4.1 Changes in tropical tuna purse seiners' strategies

In the Atlantic and Indian Oceans, the proportion of fishing sets on FOBs gradually increased over 2003-2014, indicating that the Floating Object strategy progressively became more important than the Free Swimming School strategy (Figure 4.3) . The proportion of fishing sets on FOBs was generally higher in the Indian Ocean than in the Atlantic Ocean. In 2003, European Union purse seiners made 41.8% (S.D . among vessels of 13.2) and 50.9 % (S.D. 19.8) of their fishing sets on FOBs in the Atlantic and Indian Oceans, respectively. In 2014, these proportions reached 59.0% (S.D. 17.6) and 70.6% (S.D. 16.7), representing a relative increase of 41.1% and 38.7%, respectively. In each ocean, there were inter-annual and inter-seasonal variations in these proportions (Figure 4.3 a & b, respectively). FOBs dominated the strategy of purse seiners from August to December in the Atlantic Ocean. The month of October was the main month for FOB fishing with 63.2% (S.D. 14.6) of monthly fishing sets, while April was the main month of FSC fishing with 57.1% (S.D. 11.4) of the fishing sets . In the Indian Ocean, the seasonality was stronger than in the Atlantic Ocean. In this ocean, there were two main seasons for FOB fishing: August to October (with up to 80.4% of the fishing sets in August, S.D. 9.0) and March to April (with up to 61.1% of the fishing sets in March, S.D. 13.9).

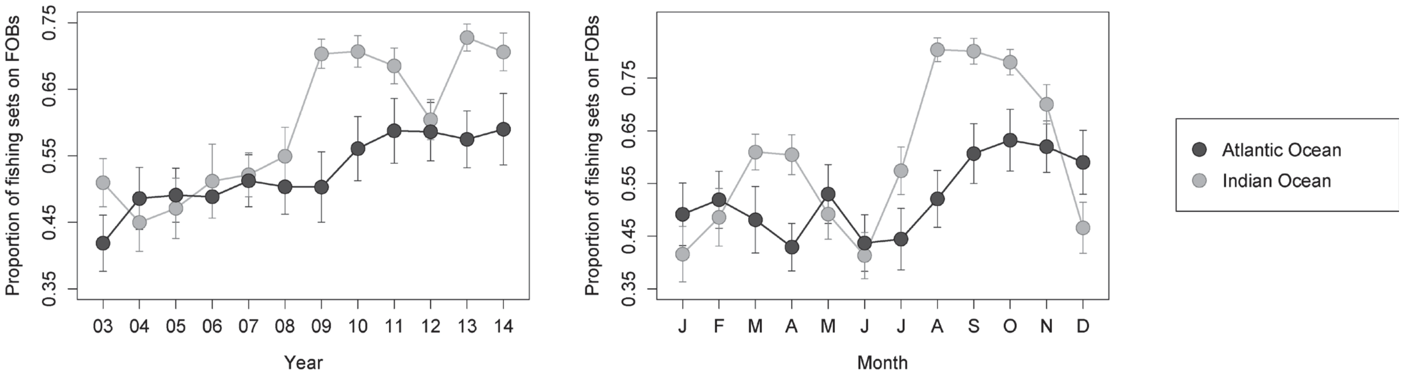


Figure 4.3: Effect of the year (left panel) and the month (right) on the strategies of purse seiners with FOBs from 2003 to 2014 in the Atlantic and Indian Oceans. Error bars represent the standard error of the mean.

Variables vessel characteristics and support vessels had also a significant effect on the proportions of fishing sets on FOBs. These proportions generally increased with the length of purse seiners, the use of support vessels, and were higher for the Spanish Fleet than the French fleet (Figures 4.4 and 4.5). In the Atlantic Ocean, there was no significant difference between Spanish purse seiners of different length but Spanish purse seiners made a significantly higher proportions of their fishing sets on FOBs than French purse seiners (p value < 0.001 for all pairwise comparisons). There was generally no significant difference in strategies with FOBs between French vessels of different length, except between categories 59-72 m and 73-94 m (with a relative difference of 25.5%, p value < 0.001).

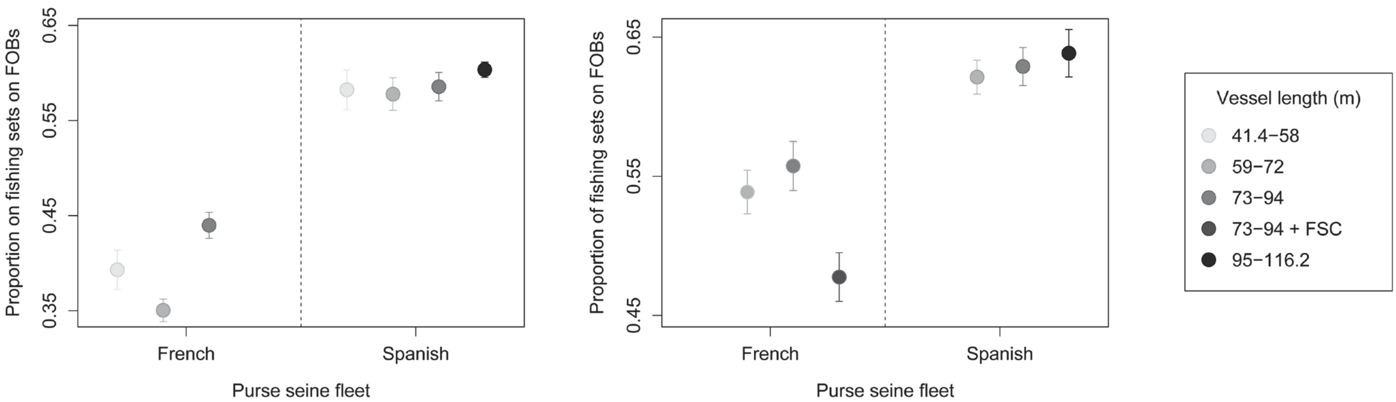


Figure 4.4: Effect of the fleet and the size of purse seiners on the strategies of purse seiners with FOBs from 2003 to 2014 in the Atlantic (left panel) and Indian Oceans (right panel). Error bars represent the standard error of the mean.

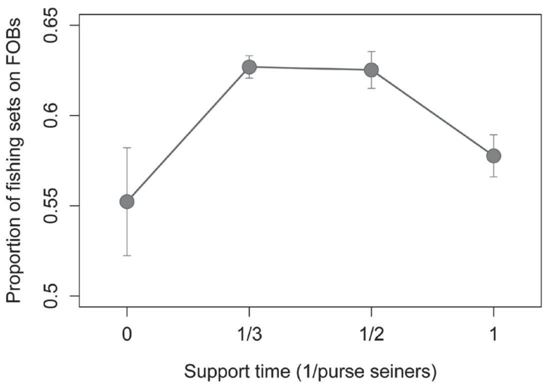


Figure 4.5: Effect of support vessels on the strategies of purse seiners with FOBs from 2003 to 2014 in the Indian Ocean. Error bars represent the standard error of the mean.

In the Indian Ocean, where the purse seine fleet is composed of larger vessels than in the Atlantic Ocean, differences between smallest and largest vessels were lower and not significant (3.5% for the French fleet and 2.8% for the Spanish fleet respectively). Differences between purse seiners were almost exclusively related to the fleet, as Spanish purse seiners were significantly more specialized in FOB fishing ($p < 0.001$) with 63.0% of fishing sets on FOBs (SD 21.0) against 53.3% for French purse seiners (SD 21.8). Vessels of the French fishing company know to target FSC had the lowest proportion of fishing sets on FOBs (47.8%, S.D. 21.4). Purse seiners benefiting from a support vessel generally made a greater proportion of their fishing sets on FOBs. Surprisingly, purse seiners sharing a support vessel with another purse seiner (support time ½) had a significantly clearer FOB strategy than those benefiting from a “full time” support vessel (support time 1, p value < 0.001), with 62.7% (21.3) and 57.8% (S.D. 21.8) and of fishing sets on FOBs.

4.4.2. Factors affecting the efficiency of tropical tuna purse seiners

After accounting for abundance conditions with the effect of the month and the year, vessel characteristics (Figure 4.6 and 4.7), support vessels (Figure 4.8) and strategies with FOBs (Table 4.3) generally had a significant effect on the efficiency of purse seiners. In the Atlantic and Indian Oceans, larger vessels caught larger amounts of skipjack, yellowfin and bigeye tuna per day (CPUE1), per fishing set (CPUE2), per travelled distance (CPUE3), made larger numbers of fishing sets per day (SPUE) and travelled larger distances per day (DPUE). For example, in terms of catch per fishing set (CPUE2), the most common measure of CPUE for tropical tuna purse seine fleets, the largest French purse seiners were on average 11.5% (not significant, p-value = 0.9) and 16.5% (p-value = 0.04) more efficient than the smallest French purse seiners in the Atlantic and Indian Oceans, respectively. For the Spanish fleet, the difference between smallest and largest vessels reached 32.5% in terms of CPUE2 in the Indian Ocean but it was found to be not significant (p-value = 0.8). However in the Atlantic Ocean, the largest vessels of 95-116.2 m, that were active only 3 years in this ocean to avoid piracy in the Indian Ocean, were less efficient than those of 73 to 94 m.

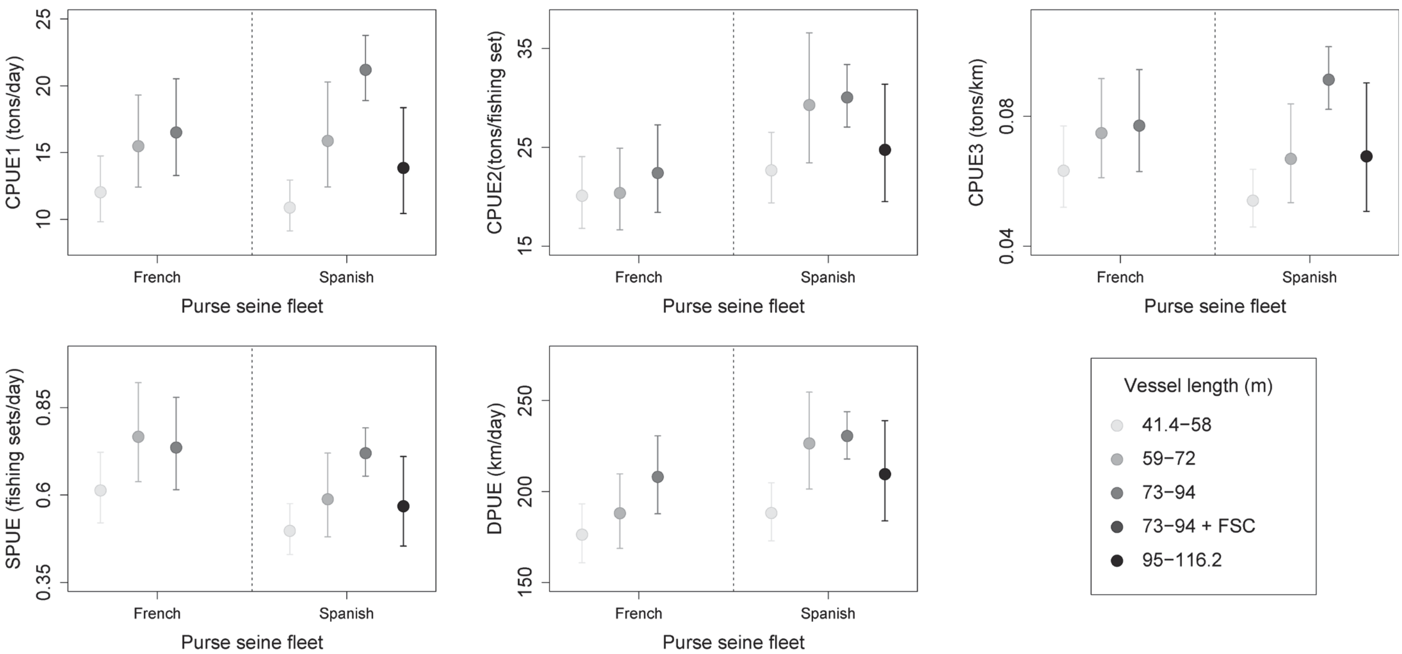


Figure 4.6: Effect of vessel size and purse seine fleet on the efficiency of tropical tuna purse seiners of the Atlantic Ocean over 2003-2014. Error bars represent the standard error of the mean.

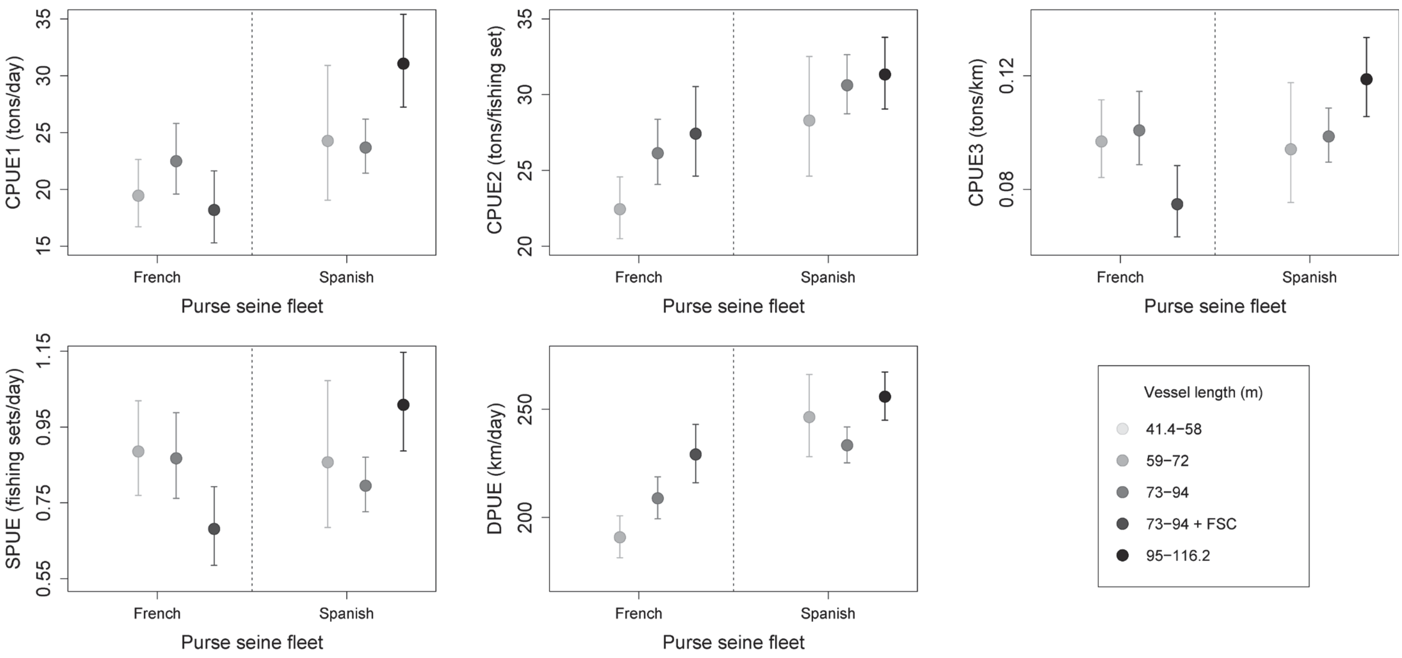


Figure 4.7: Effect of vessel size and purse seine fleet on the efficiency of tropical tuna purse seiners of the Indian Ocean over 2003-2014. Error bars represent the standard error of the mean.

For the whole purse seine fleet, the increasing use of FOBs had a significant positive effect on the catch per day, catch per fishing set and travelled distance while the catch per travelled distance and the number of fishing sets per day decreased (Table 4.3). Specific strategies of fishing companies and fishing fleets also had an effect on the efficiency of tropical tuna purse seiners. In the Indian Ocean, French purse seiners 73 to 94 meters in length designed to target FSC tropical tunas were generally less efficient (in terms of total catch) than other French purse seiners of the same size. Their efficiency decreased of 19.1% in terms of CPUE1, 25.8% in terms of CPUE3 and 21.5% in terms of SPUE. In addition, Spanish purse seiners were more efficient than French purse seiners of the same size in terms of CPUE1, CPUE2 and DPUE, but their efficiency decreased in terms of CPUE3 and SPUE. Overall, our results indicate that purse seiners increasing the use of FOBs were more efficient at maximizing their catches by decreasing the number of null fishing sets due to FSC fishing (SPUE) and undertaking regular fishing sets (CPUE1 and CPUE2), though part of the distance they travelled during their fishing trips did not allow to maximize catches (CPUE3).

Table 4.3: effect of the proportion of fishing sets on FOBs on the five dimensions of the efficiency of tropical tuna purse seiners.

Efficiency measure	Atlantic Ocean	Indian Ocean
CPUE1	n.s. (p= 0.17)	0.18 (p= 3.96e-6)
CPUE2	0.30 (p= 2.2e-16)	0.44 (p= 2.2e-16)
CPUE3	-0.27 (p= 3.11e-10)	n.s. (p= 0.29)
SPUE	-0.25 (p= 2.2e-16)	-0.28 (p= 2e-16)
DPUE	0.24 (p= 2.2e-16)	0.19 (p= 2.2e-16)

n.s. indicates that the parameter was not significant (p> 0.01, chi-squared test). Response and predictor variables were log transformed.

Finally, the use of support vessels had a significant effect on the efficiency of tropical tuna purse seiners of the Indian Ocean, except in terms of travelled distance (DPUE, Appendix C3). Purse seiners benefiting from their own support vessel (support time = 1) made 12.3% more catch per day, 15.3% more catch per fishing set and 12.3% more catch per distance than purse seiners without support vessel (support time = 0). In terms of numbers of fishing sets per day, there was no clear relationship between the efficiency of tropical tuna purse seiners and support time, the most efficient purse seiners being those sharing their support vessel with another purse seiner (support time = ½) and the least efficient being those with a full time support vessel.

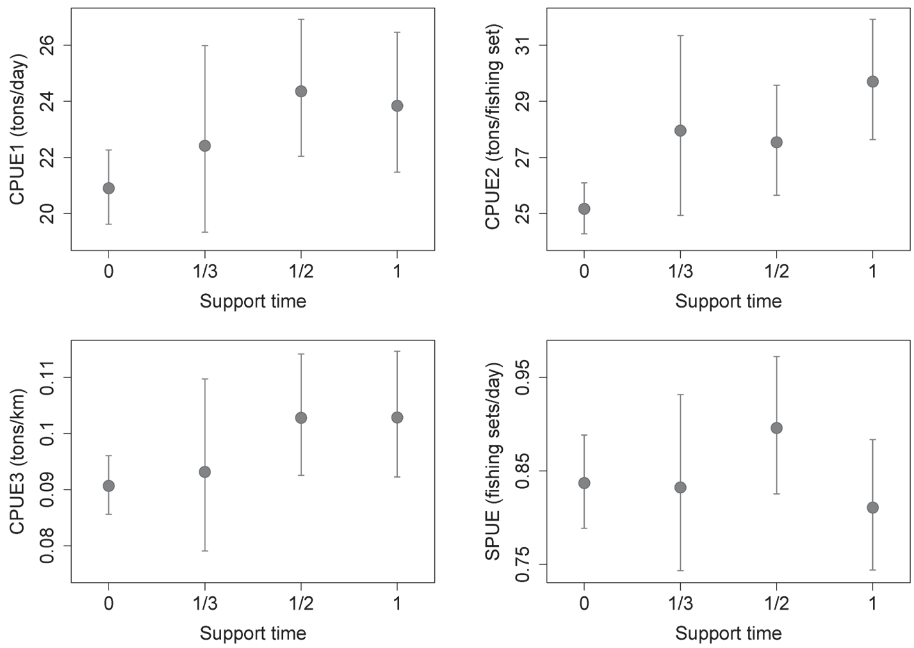


Figure 4.8: Effect of support vessels on the efficiency of tropical tuna purse seiners of the Indian Ocean over 2003-2014. Error bars represent the standard error of the mean. The effect of support time on DPUE was found to be not significant, results are not presented here.

4.4.3. Evolution of the fishing efficiency of the tropical tuna purse seine fleet

In the Atlantic and Indian Oceans, the total efficiency of the tropical tuna purse seine increased in terms of catch per day (CPUE1), catch per fishing set (CPUE2), catch per distance (CPUE3), fishing sets per day (SPUE) and travelled distance (DPUE) (Figure 4.10). Among the 5 dimensions of efficiency analysed in this study, CPUE2 increased fastest in the two oceans with an increase of 18.8% in the Atlantic Ocean and 26.3% in the Indian Ocean in 11 years, representing an annual increase of 1.6% and 2.2%, respectively. SPUE remained almost constant in the Atlantic Ocean with an increase of +0.8% and strongly decreased in the Indian Ocean with a variation of -9.4% (Figure 4.9, Table 4.4).

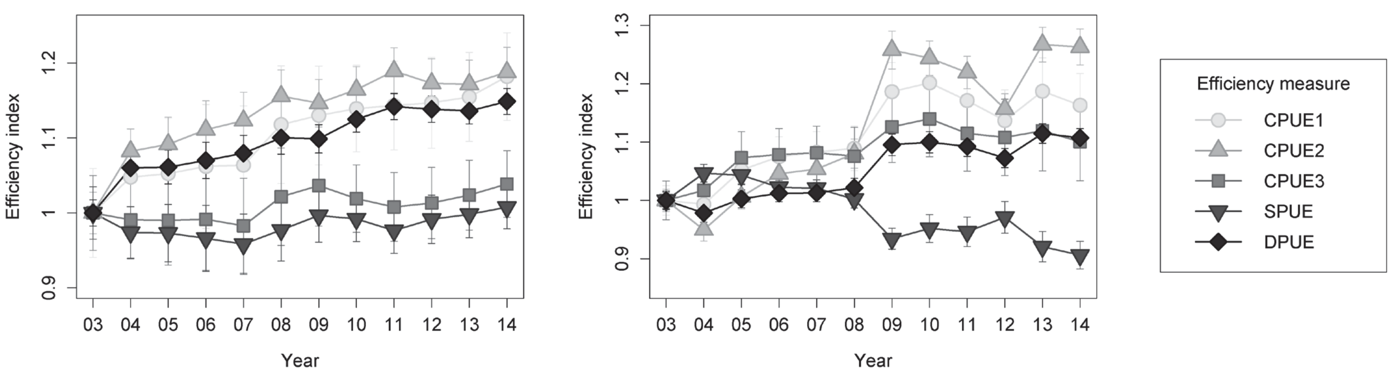


Figure 4.9: Evolution of the total efficiency of purse seiners over 2003-2014 in the Atlantic Ocean (left panel) and the Indian Ocean (right panel) Error bars represent the standard error of the mean.

Table 4.4: changes in the total efficiency of tropical tuna purse seiners (ΔI) of the Atlantic and Indian Oceans over 2003-2014 and contribution of technical (ΔI_{TE}, size of purse seiners, fleet and support vessels) and strategic changes (ΔI_{SE} , proportion of fishing sets on FOBs)

	Atlantic Ocean			Indian Ocean		
Efficiency measure	**ΔI**	**ΔI_{TE}**	**ΔI_{SE}**	**ΔI**	**ΔI_{TE}**	**ΔI_{SE}**
CPUE1	+18.2%	+18.2%	n.s.	+16.3%	+9.7%	+6.0%
CPUE2	+18.8%	+7.0%	+15.5%	+26.3%	+9.4%	+15.4%
CPUE3	+3.9%	+14.0%	-8.9%	+10.0%	+10.0%	n.s.
SPUE	+0.8%	+9.9%	-8.3%	-9.4%	-0.7%	-8.7%
DPUE	+14.9%	+5.6%	+8.7%	+10.7%	+3.9%	+6.5%

n.s. indicates that the parameter was not significant (p> 0.01, chi-squared test). Response and predictor variables were log transformed.

4.5 Discussion

In this study, five different dimensions of the efficiency of EU purse seiners (catch per day, catch per fishing set, catch per distance, number of fishing sets per day and travelled distance per day) were analysed to measure fishing efficiency over 2003-2014 in the Atlantic and Indian Oceans. They were chosen to represent the ability of purse seiners to optimize their catches (CPUE1, CPUE2, CPUE3), the size of their fishing sets (CPUE2), the duration between successive fishing sets (SPUE) and the detection of tuna schools by the appropriate choice of a fishing ground (DPUE). Their evolution was assessed through regression models (GLMs and GLMMs) to measure the contribution of vessel characteristics, use of support vessels and strategies with FOBs to the individual efficiency of tropical tuna purse seine fleets. Results indicated a strong progression of the FOB strategy on the FSC strategy with an annual rate of +3.2% and +3.0% of the proportion of fishing sets on FOBs in the Atlantic and the Indian Oceans, respectively. Larger purse seiners benefiting from support vessels, that were generally more efficient than smaller purse seiners without support vessel were introduced. These technical and strategic changes contributed to a significant increase in the total efficiency of tropical tuna purse seine fleets that reached 1.6% per year in the Atlantic Ocean and 2.2% per year in the Indian Ocean in terms of catch per fishing set (CPUE2).

4.5.1 Understanding the individual efficiency of tropical tuna purse seiners

To measure these changes, the choice was made to work at the scale of fishers' strategies. Individual efficiency was measured at the scale of the month, assumed to be representative of the medium term decision making of skippers, i.e. of their strategies (Torres-Irineo et al., 2014). In addition, as a typical month is a succession of tactics (i.e. short term decisions) on FOBs and FSC that cannot be clearly separated even at the scale of the day, activities on FOBs were not separated from activities on FSC in the five measures of efficiency. Similarly, the total catch of the three species (skipjack, yellowfin and bigeye tuna) was considered as the species composition of the catch is highly variable in time and space in both oceans. As a consequence, the results we obtain can only be used to assess changes in the strategies and efficiency of tropical tuna purse seiners at the scale of the ocean basin and of combination of two different métiers (fishing on FOBs vs fishing on FSC). However, this general approach can be seen as a first major step to monitor recent changes in the efficiency of tropical tuna purse seiners in a context of increasing use of FOBs (Maufroy et al., 2017 -

chapter 2) and support vessels (Assan et al., 2015).

Nevertheless, there are a number of limitations that could not be addressed in this study. Due to strong collinearity (Appendix C1), most of the available variables were discarded from the analyses, after initial examination of their individual contribution to the percentage of deviance explained by these variables in the models. However, as larger vessels generally benefited from a support vessel, adopted a dominant FOB strategy and progressively replaced smaller purse seiners (section 4.4.1, Appendix C1), the estimated effects of vessel characteristics, support vessels and strategies with FOBs may be biased .

Overall, the models indicated that the largest purse seiners were generally the most efficient. Such effects of the size of fishing vessels have long been described in various other fisheries (Hilborn and Ledbetter, 1985; Kimura, 1981; Marchal et al., 2001). There was only one exception for the largest purse seiners in the Atlantic Ocean (95-116.2 m) that were less efficient than medium sized purse seiners (73-94 m). This may result from particularly poor conditions of tropical tuna stocks in the Atlantic Ocean that render too large purse seiners less efficient. Well known differences between the Spanish and the French purse seine fleets, due to differences in vessel size (Spanish vessels being larger than French vessels) and specialization of Spanish skippers in FOB fishing (Guillotreau et al., 2011) were not only confirmed by our results but also quantified.

4.5.2. The success of the FOB strategy over the FSC strategy

Over 2003-2014, fishers increased their proportion of fishing sets on FOBs at an annual rate of 3.2% and 3.0% in the Atlantic and the Indian Oceans, respectively. Increasing the proportion of fishing sets on FOBs had a positive effect on catch per day (CPUE1), catch per fishing set (CPUE2) and distance per day (DPUE). On the contrary, adopting a dominant FOB strategy reduced the individual efficiency in terms of fishing sets per day (SPUE), though this decrease could also indicate a reduction in the number of null fishing sets. In addition in the Atlantic Ocean, the increasing proportion of fishing sets on FOBs had a negative effect on the catch per distance (CPUE3). Travelling longer distances did not improve catches, indicating that the “energetic cost” of fishing on FOBs is higher than on FSC, though it has often been advocated to FOBs could be used to reduce fuel consumption (Parker et al., 2015).

Parallely during this period, fishing companies progressively redirected their investments towards a dominant FOB strategy with purse seiners of increasing size and an increasing use of support vessels. This was true for all but one fishing company of the Indian Ocean that began to operate in 2009 with a clear Free Swimming School strategy oriented towards the production of high quality FSC tuna for the Asian market. This specific strategy logically led to lower proportions of fishing sets on FOBs but also to a lower efficiency in terms of catch per day, catch per fishing set, catch per distance, and distance per day. These differences were also observed at the scale of the fleet, as French purse seiners generally targeting more FSC than Spanish vessels were also found less efficient than Spanish purse seiners in terms of overall productivity. Considering differences in market price between large yellowfin and skipjack in relation to their intended use (i.e. canning or loins and steaks) would provide insight into the economic profitability of each fishing strategy but was beyond the scope of the present study.

Though FSC catches are generally dominated by the high market value yellowfin tuna and FOB catches by the lower market value skipjack tuna, the FOB strategy progressively supplanted the FSC strategy since the beginning of the 2000s. For some skippers, being able to 'hunt' the large and fast yellowfin tunas may be more rewarding but is also more risky than 'gathering' tuna 'cultivated' at FOBs, even though this may result in lower catches (Guillotreau et al., 2011). However, with higher success rates on FOBs (50% against 90%) and higher catch rates than on FSC (Fonteneau et al., 2013), the FOB strategy may have become more profitable, especially the market price of yellowfin tuna was low. This may be even truer for Spanish vessels for which the remuneration is not based on the commercial value of the catch but on the tonnage and who therefore receive little economic incentive to catch large yellowfin tuna in FSC. Combined with a progressive deterioration the state of yellowfin tuna stocks in the Atlantic and Indian oceans (ICCAT, 2015; IOTC, 2015), fishing skipjack tuna under FOBs had all the chances to become the dominant strategy.

4.5.3 Evolution of the total efficiency of tropical tuna purse seine fleets

Results indicated a progression of the total efficiency of purse seine fleets at a rate of 0.34% - 1.53% and 0.87% - 2.15% per year in the Atlantic and the Indian Oceans, respectively. This may seem relatively low compared to recent estimates of a 3.8% annual increase of fishing power in the Western Pacific Ocean from 1994 to 2010 (Tidd et al., 2016) or to the general assumption that fishing power increases at a rate of 2 to 3% per year used in tuna RFMOs. However, other studies include the 1980s or the 1990s, corresponding to the introduction of major technological innovations (Itano et al., 2004; Torres-Irineo et al., 2014) or to the fast development of FOB fishing (Fonteneau et al., 2000). The magnitude of changes is logically lower during recent years than during the development of the fishery.

Indices of total efficiency were then decomposed into a strategic efficiency (SE) measuring the contribution of strategies with FOBs and a technical efficiency (TE) measuring the contribution of vessel characteristics and support vessels to the total efficiency of purse seine fleets. Due to data availability, such information on strategies with FOBs and support vessels are rarely taken into account by tuna RFMOs. This is yet crucial as strategic efficiency had a strong influence on the total efficiency of tropical tuna purse seiners, increasing of 6% in terms of catch per day (CPUE1), 15.4 - 15.5% in terms of catch per fishing set (CPUE2) and 6.5 – 8.7% in terms of distance per day (DPUE). The effect of the use of FOBs may even be more important than the values estimated here. As the proportion of fishing sets on FOBs is strongly correlated with the year, the month, vessel characteristics and the use of support vessels, the effect of the relative use of FOBs and FSC may be underestimated by the models, as indicated by the relatively low percentage of deviance explained by this variable (Appendix C3). In addition, the proportion of fishing sets on FOBs may be the result of fishers' strategies and particular abundance conditions, inducing a potential underestimation if the effect of the year captured some of the effect of strategies with FOBs. Number of active GPS buoy-equipped FOBs may have been a better explanatory variable, but this information was only available at the scale of the quarter and was anonymised for the Spanish purse seine fleet.

On the other hand, information on the collaboration between purse seiners and their support vessels is rarely available, even to tuna RFMOs that do not require fishing fleets to report this information. Our results indicate that this information is of primary importance, as support vessels contributed to an increase in the individual efficiency of purse seiners of 12.3% to 15.3% and an increase of 1.2% to 5.7% of the total efficiency of tropical tuna purse seine fleets over 2003-2014. This increase can be explained by the multiple roles of support vessels (Arrizabalaga et al., 2001; Pallares et al., 2002; Ramos et al., 2010). First, as they are in charge of deploying new dFADs and replacing GPS buoys of FOBs already drifting at sea, they provide the opportunity to purse seiners to monitor more FOBs at the same time, therefore offering more options to catch fish to the vessels they assist. Second, as support vessels are also in charge of monitoring the amount of fish aggregated under FOBs and signalling potential interesting fishing sets, they can contribute to the reduction of null fishing sets (SPUE) and a higher size of fishing sets (CPUE2) identified here, which in turn result to a higher catch per day (CPUE1).

Our results further underline the need for detailed and fine scale information on the GPS buoy-equipped FOBs and support vessels by tropical tuna purse seine fleets for an appropriate monitoring and management of the fishery. In a context of growing pressure for the management of the purse seine fishery, mainly due to the consequences of its increasing use of FOBs (Fonteneau and Chassot, 2014), having access to detailed information on support vessel and FOB use could be a first step towards a more sustainable exploitation of tropical tunas.

Appendix C1: Details on the variables used in the GLMs and GLMMs

Correlation between vessel length and other characteristics of purse seiners

The capacity and the length of purse seiners were strongly correlated in the Atlantic and Indian Oceans over 2003-2014. Therefore, only one of the two variables could be used in the GLMs and the GLMMs. Similar observations were made on the relationship between the length of purse seiners and other vessel characteristics, larger vessels generally having a higher carrying capacity, higher engine power and higher speed

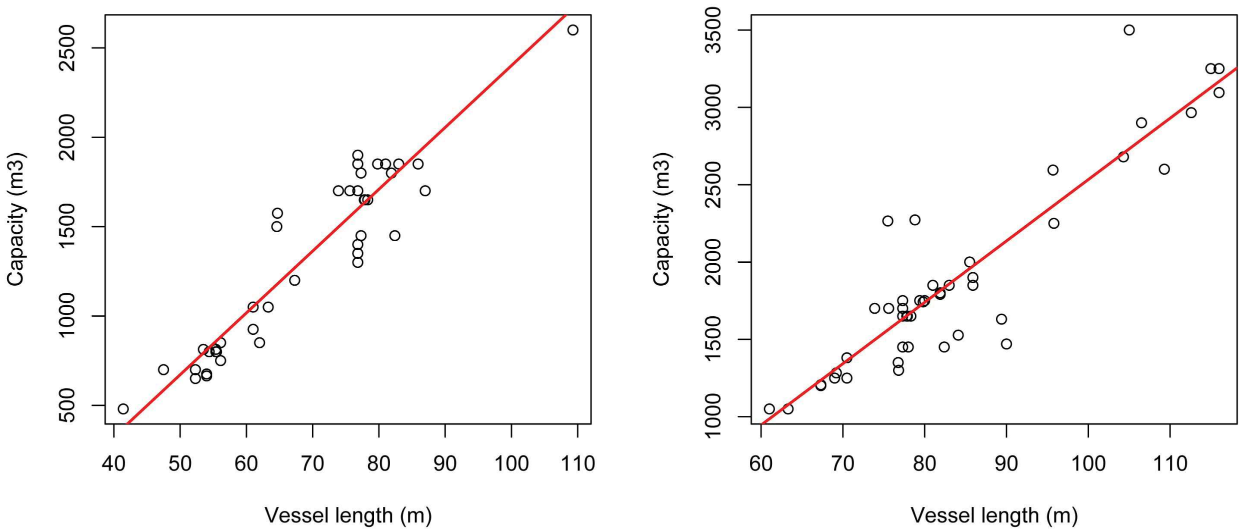


Figure C1: relationship between the capacity and the length of purse seiners during 2003-2014 in the Atlantic Ocean (left panel) and the Indian Ocean (right panel)

Construction of categories of vessel length and purse seine fleets

The capacity and the length of purse seiners were strongly correlated in the Atlantic and Indian Oceans over 2003-2014. Therefore, only one of the two variables could be used in the GLMs and the GLMMs. Similar observations were made on the relationship between the length of purse seiners and other vessel characteristics, larger vessels generally having a higher carrying capacity, higher engine power and higher speed during search activities .

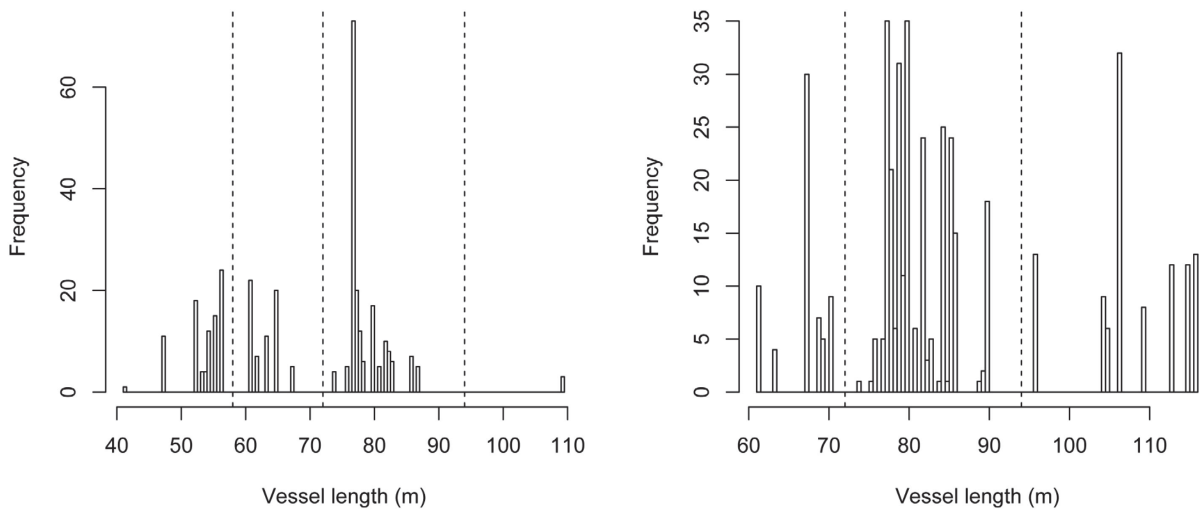


Figure C2: histogram of the length of purse seiners during 2003-2014 in the Atlantic Ocean (left panel) and the Indian Ocean (right panel)

Categories of vessel characteristics were built using histograms of vessel length. 4 categories were identified: 41.2 m to 58 m / 59 m to 72 m / 73 m to 95 m/ 95 m to 116.2.

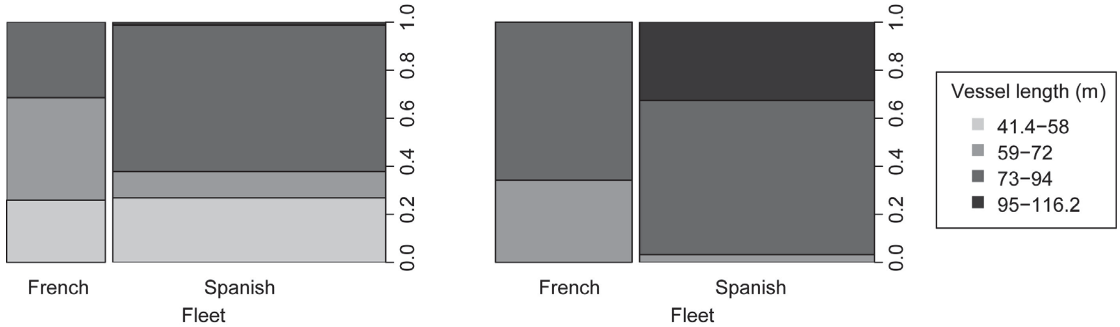


Figure C3: relationship between the length of purse seiners and the fleet during 2003-2014 in the Atlantic Ocean (left panel) and the Indian Ocean (right panel)

Over 2003-2013, purse seiners of the Atlantic Ocean were generally smaller than those of the Indian Ocean (Figure C3) with only two purse seiners of the class 95-116.2 m being present in the Atlantic Ocean and purse seiners of the class 41.2-58 m being absent from the Indian Ocean. In both oceans, the average size of Spanish purse seiners was generally higher than the length of French purse seiners. As the length of purse seiners and their fleet were highly correlated, and Spanish purse seiners generally adopted a dominant FOB strategy while French purse seiners used more FSC (Guillotreau et al., 2011), a mixed variable "vessel length – fleet" was built (Table C1).

An additional category of French purse seiners was added to this list. Among purse seiners of 73 to 94m, vessels of one French fishing company were designed to target FSC tuna. For these factory vessels, carrying capacity is lower than other vessels of the same size, to produce high quality deep frozen yellowfin tuna. They were grouped into the category "Vessel length 73 – 94 m + FSC".

Table C1: categories of "vessel length –fleet"

	French fleet	Spanish fleet
Vessel length 41.2 – 58 m	1	5
Vessel length 59 – 72 m	2	6
Vessel length 73 – 94 m	3	7
Vessel length 73 – 94 m + FSC	4	No vessel
Vessel length 95 – 116.2 m	No vessel	8

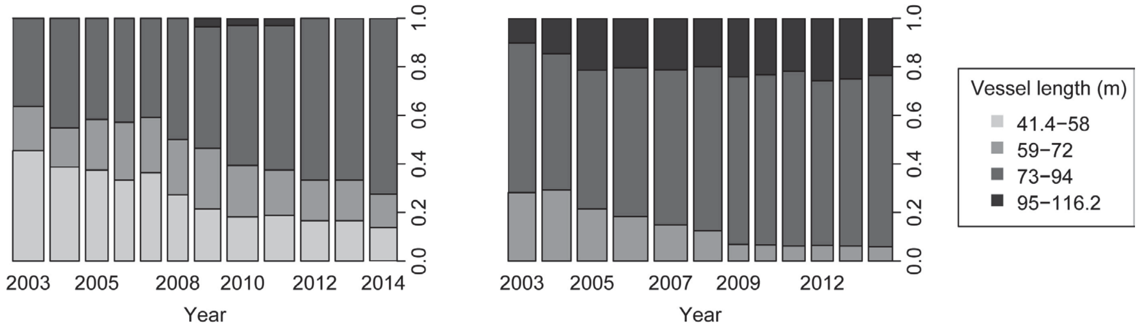


Figure C4: evolution of the size of purse seiners over 2003-2013 in the Atlantic Ocean (left panel) and over 2003-2014 in the Indian Ocean (right panel).

In the Indian Ocean, there is also a relatively strong correlation between the size of purse seiners and their use of support vessels (Cramer's V coefficient of 0.46), the use of support vessels being more important for larger vessels. We can also observe a moderate correlation between the year and the use of support vessels (Cramer's V coefficient of 0.25). Over time, more purse seiners are assisted by support vessels and the most recent purse seiners have higher chances of benefiting from a shared support vessel.

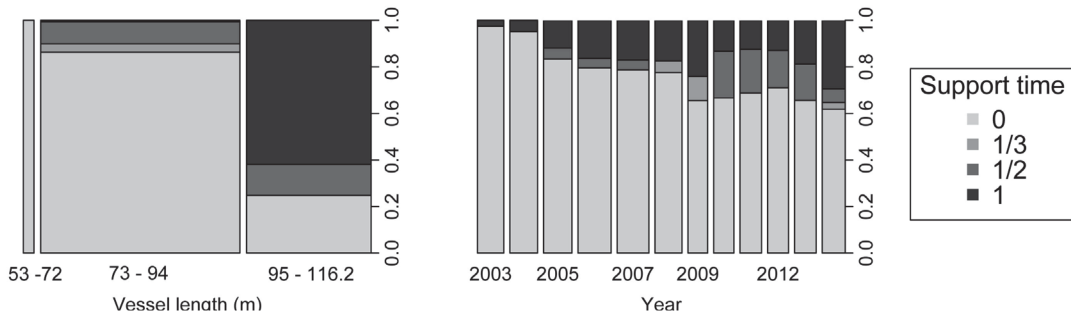


Figure C5: relationship between support time and vessel length (left panel) and the year (right panel) in the Indian Ocean

Appendix C2: details on the strategy GLMs

The proportion of fishing sets on FOBs was used to represent changes in the relative use of FOBs and FSC of tropical tuna purse seine fleets. As these proportions were 0 and 1 inflated, GLMs relating strategies with FOBs (P) to the vessel characteristics (C), use of support vessels (S), the year (Y) and the month (M) were built using gamlss package, allowing to use a 0-1 inflated beta distribution.

Proportion of fishing sets on FOBs in the Atlantic Ocean

The following GLM model was fitted on the monthly proportion of fishing sets on FOBs of tropical tuna purse seiners of the Atlantic Ocean over 2003-2014:

$$\text{logit}(P) \sim Y + M + Y{:}M + C + \varepsilon$$

Each variable was selected by the stepGAIC procedure and a significant effect on the monthly proportion of fishing sets on FOBs (Table C2). Diagnostic plots confirmed the goodness of fit of the model, though there was remaining hereroscedasticity in the residuals of the model.

Table C2: selection of the variables in the strategy GLM in the Atlantic Ocean (stepGAIC procedure of package gamlss)

Step	Df	Deviance	Resid. Df	Resid. Dev	AIC
NULL			3292	2953.261	2961.261
+category	6	302.1804	3286	2651.081	2671.081
+month	11	172.7597	3275	2478.321	2520.321
+ year	11	81.2086	3264	2397.112	2461.112
+year:month	121	421.0614	3143	1976.051	2282.051

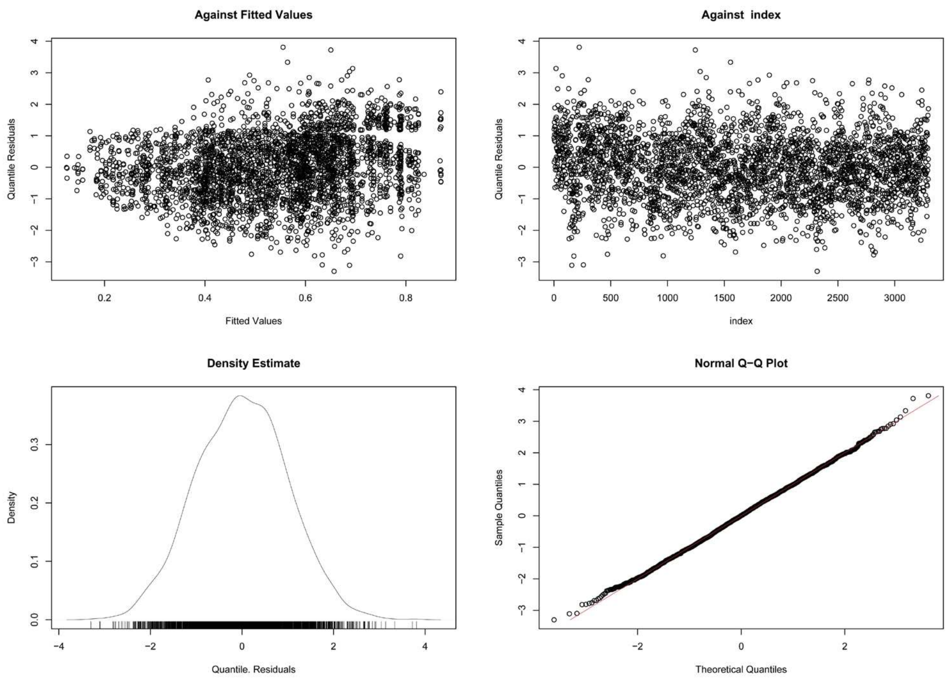


Figure C6: diagnostic plots for the GLM on strategy with FOBs in the Atlantic Ocean

Proportion of fishing sets on FOBs in the Indian Ocean

The following GLM model was fitted on the monthly proportion of fishing sets on FOBs of tropical tuna purse seiners of the Indian Ocean over 2003-2014:

$$\text{logit}(P) \sim Y + M + Y{:}M + C + S + \varepsilon$$

Each variable was selected by the stepGAIC procedure and a significant effect on the monthly proportion of fishing sets on FOBs (Table C3). Diagnostic plots confirmed the goodness of fit of the model.

Table C3: selection of the variables in the strategy GLM in the Indian Ocean (stepGAIC procedure of package gamlss)

Step	Df	Deviance	Resid. Df	Resid. Dev	AIC
			4784	2917.691	2925.691
+month	11	1414.33284	4773	1503.3582	1533.3582
+year	11	821.09735	4762	682.2608	734.2608
+year:month	121	1618.78388	4641	-936.523	-642.523
+category	5	507.27137	4636	-1443.7944	-1139.7944
+support time	3	55.86176	4633	-1499.6562	-1189.6562

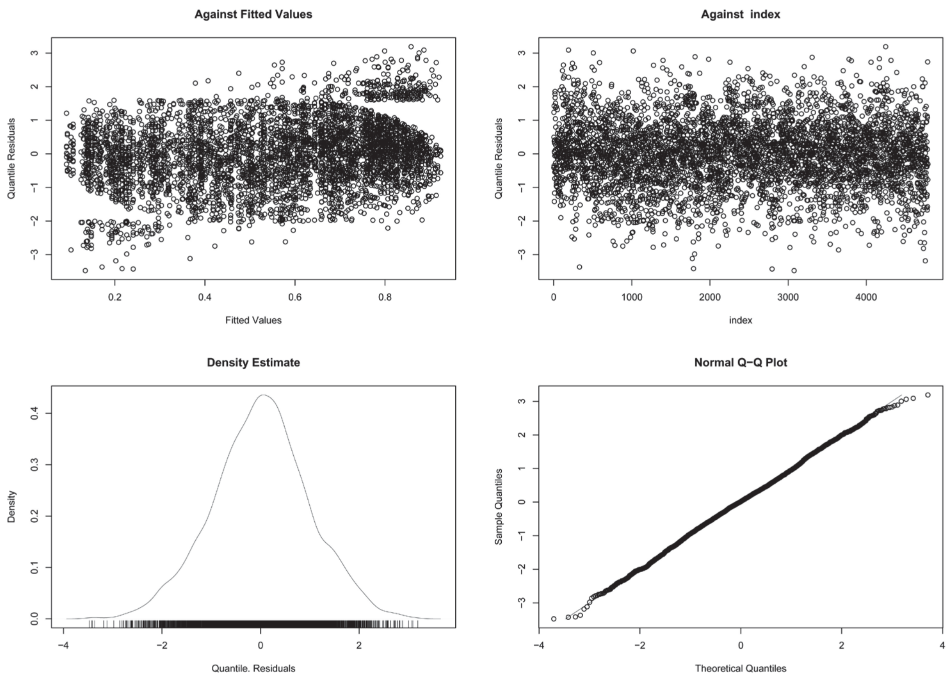


Figure C7: diagnostic plots for the GLM on strategy with FOBs in the Indian Ocean

Appendix C3: details on the efficiency GLMMs

The effect of vessel characteristics (C), use of support vessels (S), proportion of fishing sets on FOBs (P), year (Y) and month (M) and the interaction between the month and the year on the efficiency of tropical tuna purse seiners were tested with GLMMs. Five different models were built for CPUE1, CPUE2, CPUE3, SPUE and DPUE. In this appendix, details are only provided for model CPUE2 but a similar procedure was applied to each of the five GLMMs in the Atlantic and the Indian Ocean.

CPUE2 (catch per fishing set) in the Atlantic Ocean

The following GLMM was fitted on the monthly proportion of fishing sets on FOBs of tropical tuna purse seiners of the Atlantic Ocean over 2003-2014:

$$\log(E) \sim Y + M + Y{:}M + C + P + \varepsilon$$

Each variable was selected using a stepwise AIC procedure and a significant effect on CPUE2 (Table C4). Diagnostic plots confirmed the goodness of fit of the model.

Table C4: summary of the model CPUE2 in the Atlantic Ocean, fixed effects (chi-squared test provided by the function Anova of car package)

	Chisq	Df	Pr(>Chisq)
year	340.248	11	< 2.2e-16
month	135.44	11	< 2.2e-16
vessel characteristics	26.019	6	2.21E-04
strategy	98.251	1	< 2.2e-16
year:month	552.477	121	< 2.2e-16

Table C5: summary of the model CPUE2 in the Atlantic Ocean, random effects (chi-squared test obtained by comparison of log likelihoods of the model with and without random effects)

	Chisq	Df	Pr(>Chisq)
Vessel identifier	0.01513	0.123	< 2.2e-16
Residual	0.19711	0.444	

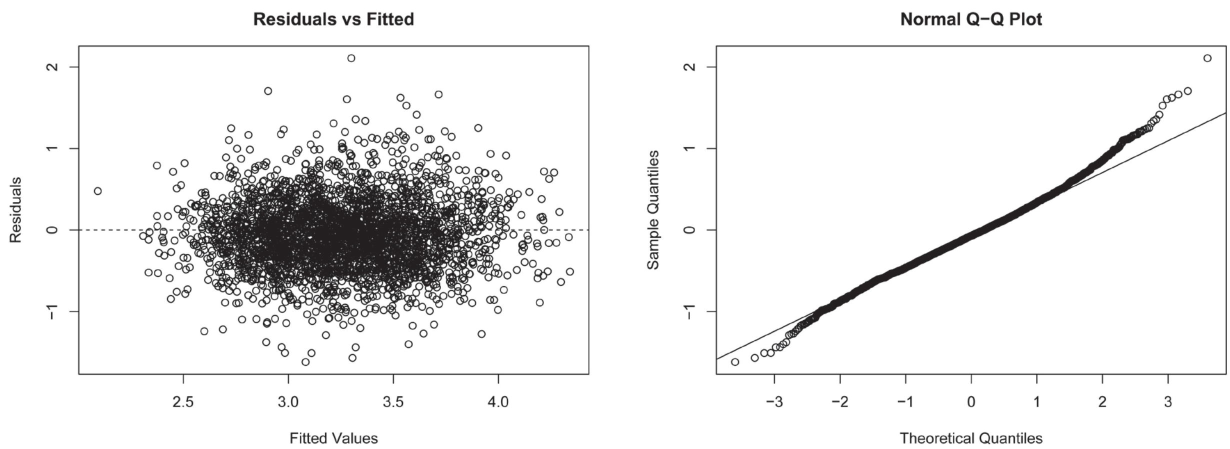


Figure C8: diagnostic plots for model CPUE2 in the Atlantic Ocean

CPUE2 (catch per fishing set) in the Indian Ocean

The following GLMM was fitted on the monthly proportion of fishing sets on FOBs of tropical tuna purse seiners of the Atlantic Ocean over 2003-2014:

$$\log(E) \sim Y + M + Y{:}M + C + S + P + \varepsilon$$

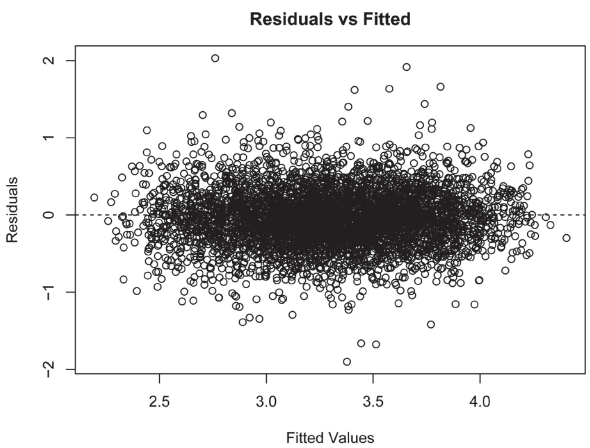
Each variable was selected using a stepwise AIC procedure and a significant effect on CPUE2 (Table S2-2). Diagnostic plots confirmed the goodness of fit of the model. Each variable was selected by the stepAIC procedure and a significant effect on the average monthly catch per day (Table C6). Diagnostic plots confirmed the goodness of fit of the model.

Table C6: summary of the model CPUE2 in the Indian Ocean, fixed effects (chi-squared test provided by the function Anova of car package)

	Chisq	Df	Pr(>Chisq)
year	1063.19	11	< 2.2e-16
month	976.47	11	< 2.2e-16
vessel characteristics	54.395	5	1.74e-10
support time	21.53	3	8.17e-05
strategy	198.948	1	< 2.2e-16
year:month	1242.369	121	< 2.2e-16

Table C7: summary of the model CPUE2 in the Indian Ocean, random effects (chi-squared test obtained by comparison of log likelihoods of the model with and without random effects)

	Chisq	Df	Pr(>Chisq)
Vessel identifier	0.01513	0.123	< 2.2e-16
Residual	0.19711	0.444	



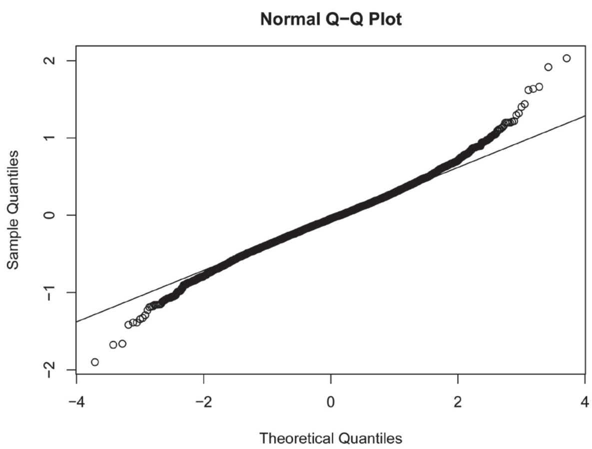


Figure C9: diagnostic plots for model CPUE2 in the Indian Ocean

Appendix C4: indices of technical and strategic efficiency

The total efficiency of tropical tuna purse seine fleets were decomposed into a technical efficiency measuring the contribution of vessel characteristics and use of support vessels and a strategic efficiency measuring the contribution of strategies with FOBs to the total effiency. Over 2003-2014, technical efficiency increased in the Atlantic Ocean and in the Indian Ocean. Strategic efficiency had a strong influence on the index of total efficiency, especially in terms of SPUE, as this index was decreasing in the two oceans.

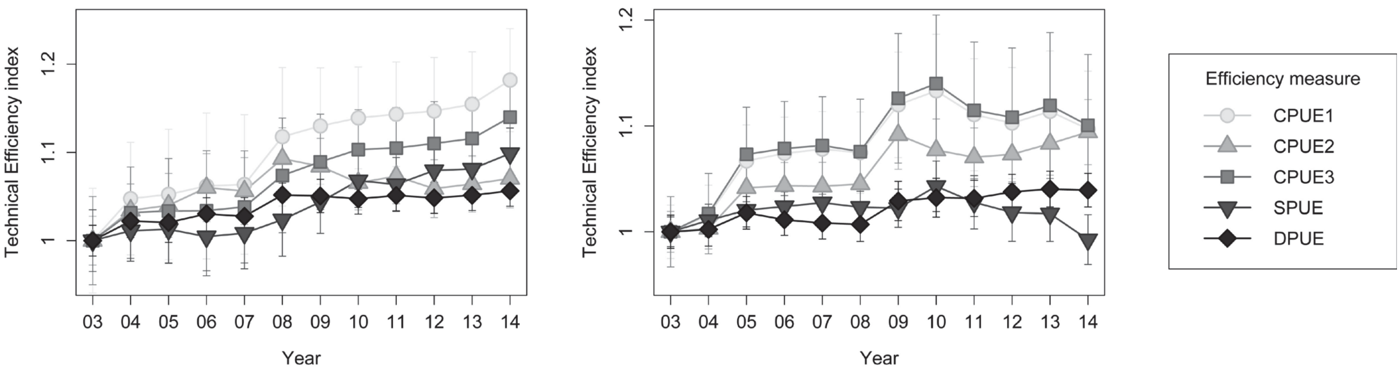


Figure C10: technical efficiency index in the Atlantic Ocean (left panel) and in the Indian Ocean (right panel) from 2003 to 2014

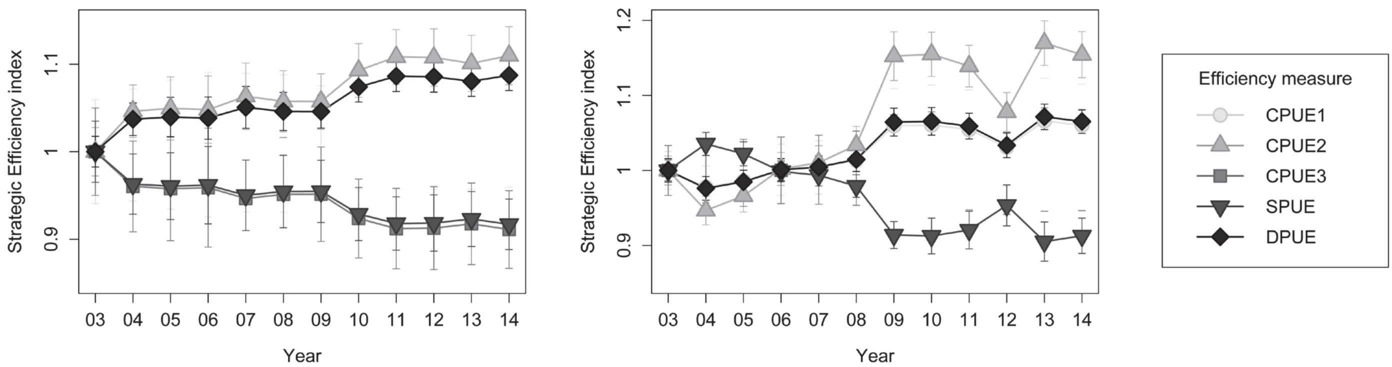


Figure C11: strategic efficiency index in the Atlantic Ocean (left panel) and in the Indian Ocean (right panel) from 2003 to 2014

CHAPTER 4:

Integrating scientific and Local Ecological Knowledge (LEK) for a better management of FOB fisheries: the case of tropical tuna purse seiners of the Indian Ocean

5.1 Objectives of the chapter

The primary objective of the present thesis was to derive information on FOB fisheries from a large variety of quantitative sources of information: GPS buoy positions, onboard observers, logbooks and VMS data. A large body of scientific knowledge was available to guide analyses of these high quality data through scientific publications and expertise of fisheries scientists. Evaluation and management of fisheries generally rely on this form of knowledge (Fischer et al., 2015; Johannes and Neis, 2007) and this was also the case of our work. However, some of this knowledge had been acquired almost twenty years ago (e.g. seasonality in dFAD buoy deployment described for example in Ariz et al., 1999) and the fishery was again entering a phase of fast changes, due to increasing numbers of dFADs and GPS buoy-equipped FOBs (this had been suggested by various authors but was still difficult to verify, e.g. Davies et al., 2014; Fonteneau and Chassot, 2014; chapter 2). Needless to say, fishers are the first witnesses of these ongoing changes. Their knowledge can be invaluable to avoid missing crucial information, avoid formulating wrong assumptions or even to foster understanding on the functioning of the fishery.

In addition, should the results of the present thesis be used to examine existing and potential management measures for the fishery, considering the sole point of view of fisheries scientists in this process seems inappropriate. Questions regarding FOB use are of interest to many different stakeholders who may have different perceptions of the fishery : fisheries scientists but also fishers, industrial operators (fishing companies, tuna canneries), managers or environmental NGOs (Airaud and Tézenas du Montcel, 2015). Within an Ecosystem Approach to Fisheries Management (EAFM), the participation of each of these groups of stakeholders is required to achieve objectives of sustainable exploitation and management of marine resources (Fischer et al., 2015; Jentoft et al., 1998; Johannes et al., 2000).

Though chapters 1 to 3 are mainly based on statistical analyses of available scientific data, a multi-disciplinary approach was therefore adopted throughout our research. Chapter 4 presents the results we obtain ed when integrating the formal scientific knowledge with the more informal knowledge of fishers in the Indian Ocean. The approach was developed as a contribution to the European project CECOFAD (Catch, Effort, and eCOsystem impacts of FAD-fishing) which involved French and Spanish fisheries scientists and fishing companies. In a context of growing pressure from environmental NGOs to prohibit the use of dFADs, this chapter compares alternative management solutions to address the problem of FOB fisheries in its multidimensional context (e.g. tuna markets, enforcement, governance).

5.2. Introduction

Fishers have long known that many species of fish, including tropical tunas, naturally associate with the objects drifting at the surface of the ocean. For centuries, they have known that fish associated with Floating Objects (FOBs) are easier to detect and easier to catch. They have long used natural FOBs as an indicator of higher abundance, better catchability and increased fish school size (Castro et al., 2002; Fréon and Dagorn, 2000; Hall, 1992), until they had the idea to mimic the natural behaviour of fish with the deployment of man-made FOBs. At the end of the 1990s, these drifting Fish Aggregating Devices (dFADs) became an important mean of catching skipjack, yellowfin and bigeye tuna by purse seiners (Fonteneau et al., 2000b). Increasing numbers of dFADs were deployed in the world oceans and specific FOB fishing technologies were introduced. Among others, the use of FOB tracking devices such as GPS buoys developed (Castro et al., 2002; Fonteneau et al., 2013) and support vessels began to assist purse seiners for dFAD deployment and searching as early as the 1990s (Arrizabalaga et al., 2001; Fonteneau et al., 2000). In all oceans, these changes have supported the fast development of purse seine fleets (Fonteneau et al., 2013; Miyake et al., 2010). In the Indian Ocean, the fishery has always been dominated by European Union purse seiners. In 2014, their catches reached more than 260,000t with almost 80% of these catches made on FOBs (Maufroy et al in preparation - chapter 3).

Over time, FOB fisheries have become an increasing source of concern for tuna Regional Fisheries Management Organizations (RFMOs) such as the Indian Ocean Tuna Commission (IOTC). Though FOBs have many positive consequences for purse seine fishing, by improving the detection of tuna schools and the success of fishing sets (Fonteneau et al., 2000b), they have also a number of negative consequences for tropical tunas and marine ecosystems (Dagorn et al., 2013). Among others, they contribute to increased catches of juveniles of yellowfin and bigeye tuna (Fonteneau et al., 2000b), strong modifications of the natural behaviour of tropical tunas (Marsac et al., 2000; Hallier and Gaertner, 2008; Sempo et al., 2013), increased levels of bycatch and discard (Amandè et al., 2011, 2012), ghost fishing of fragile species (Anderson et al., 2009; Filmalter et al., 2013) and potential damages to vulnerable habitats (Balderson and Martin, 2015; Maufroy et al., 2015, chapter 1). As the effects of the increasing use of FOBs on tropical tuna stocks remain poorly understood, there has been little specific management measures aiming at reducing their impacts, except for some time-area closures (Fonteneau et al., 2013; Fonteneau and Chassot, 2014).

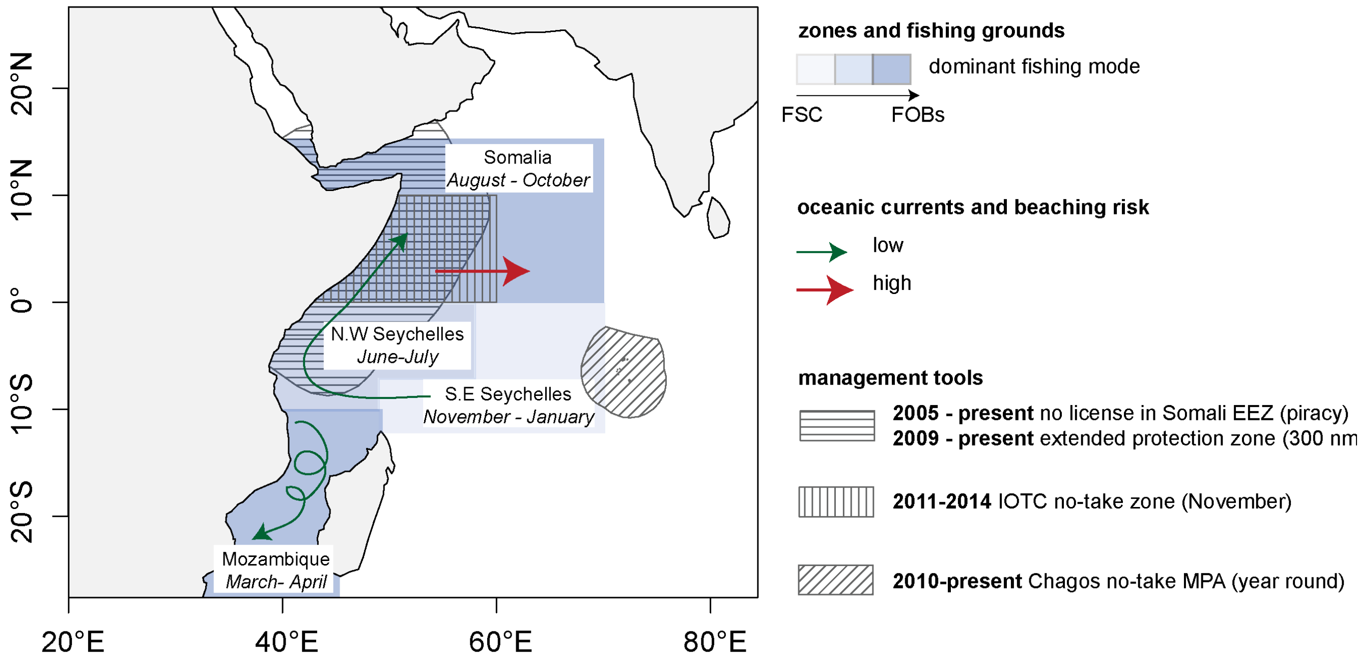


Figure 5.1: study area in the Indian Ocean. Tropical tuna purse seine fleets mainly use four fishing grounds: Mozambique Channel, NW and SE Seychelles and Somalia. Fishing on FOBs has several impacts, such as the beaching of lost dFADs (Maufroy et al. 2015 - chapter 1). Spatial management tools have been the primary response to negative consequences of FOB use.

Therefore, the number of dFADs and GPS buoy-equipped FOBs has kept increasing (Fonteneau and Chassot, 2014, Maufroy et al., 2017 - chapter 2), while fishing efficiency of tropical tuna purse seiners has continuously improved due to improving technological means (Lopez et al., 2014; Torres-Irineo et al., 2014), changes in fishing strategies with FOBs (Torres-Irineo et al., 2014, Maufroy et al. in prep- chapter 3), and support vessels (Maufroy et al. in prep- chapter 3). In recent years, considerable attention has been drawn by scientists and NGOs on the negative impacts of FOB fishing. In response to this growing pressure for specific management of FOBs, “FAD management plans” have been implemented (Res 13-08 and following resolutions) and the IOTC has adopted a limitation on the number of active GPS buoys (Res 15-08). Whilst these decisions are obviously encouraging steps, a wide variety of other management tools (e.g. fleet capacity limitation, reduction of the use of support vessels, catch quotas) could be implemented. Each of these tools may have a different efficacy, depending on their relevance to address the issues of FOB fisheries but also due to changes in the behaviour of fishers in response to their implementation.

How fishers perceive the impacts of their fishing activities and would answer to one management option or another is key to their success (Jentoft et al., 1998). Achieving a successful EAFM requires a multi-disciplinary approach combining biological, ecological and socio-economic considerations (Fischer et al., 2015) in which humans are considered as part of the ecosystem (Sáenz-Arroyo and Roberts, 2008). Since the 1990s, there is a growing consensus that fishers should be involved in management decisions (Gutiérrez et al., 2011; Jentoft et al., 1998; Jentoft and McCay, 1995) and various examples of successful “co-management” of fisheries can be cited (Pomeroy and Berkes, 1997; Hilborn et al., 2005;). Fishers have indeed a practical point of view on fisheries and the knowledge they have of the ecosystems they exploit can be a valuable source of information (Chalmers and Fabricius, 2007; Johannes et al., 2000; Moreno et al., 2007; Neis et al., 1999) to guide statistical analyses and interpret results derived from quantitative data (Johannes et al., 2000). However, in general, the informal knowledge that fishers have of their fisheries (hereafter termed ‘Local Ecological Knowledge’, LEK) has long been disregarded by fisheries scientists and managers (Johannes and Neis, 2007), leading to inappropriate management decisions (Johannes et al., 2000).

This has not been the case in tropical tuna fisheries, as purse seine skippers have regularly exchanged with fisheries scientists since the beginning of the fishery about fish behaviour (Moreno et al., 2007), technological changes (Gaertner et al., 2000; Lopez et al., 2014), fishing strategies (Guillotreau et al., 2011) or management of the fishery (Davies et al., 2015). Yet, their opinion on scientific assumptions and results has rarely been solicited to identify appropriate management tools. Here, we integrate LEK and scientific knowledge of the functioning and management of FOB purse seine fisheries in the Indian Ocean with three main objectives (i) use fishers’ knowledge to guide scientific analyses, (ii) understand the perception that fishers have of the impacts of the fishery, and finally (iii) propose adapted management tools. To achieve these objectives, we propose a two-step approach. In a first step, LEK is used to formulate appropriate assumptions on the functioning and the impacts of the fishery, in order to guide statistical analyses. In a second step, scientific knowledge obtained by the analysis of quantitative data is confronted to the opinion of purse seine skippers, in order to validate the results and identify appropriate management tools for the fishery.

5.3. Phase 1: using fishers’ knowledge to guide statistical analyses

Several sources of quantitative information were available to address a wide variety of questions on the modalities of dFADs and GPS buoy use, their consequences and their management. Logbook, VMS, observer and GPS buoy data provided complementary but not always overlapping information , due to partial coverage (e.g. when data was only available for the French fleet), differences in spatio-temporal scales (e.g. GPS buoy data was provided on a varying time scale), or the different nature of the activities that these data were describing (e.g. observer data provided information on all types of activities on FOBs while logbook data only provided information on fishing sets). To overcome the inevitable difficulties of combining these many different sources of information, LEK was gathered to eliminate wrong assumptions and guide statistical analyses.

First, quantitative data were explored, literature was reviewed and the opinion of the French fisheries scientists working on the fishery was solicited. Based on identified knowledge gaps and potential research questions, a semi-structured guide of interview was built to yield information on the modalities of dFAD and GPS buoy use (deployment, monitoring and fishing) as well as the changes having occurred for the FOB fishery (technological changes and management tools). 14 French speaking skippers, having a long experience of the functioning of the fishery in the Indian Ocean, were interviewed in June and July 2013, on their arrival in Port Victoria (Seychelles).

Interviews were conducted aboard purse seiners as informal discussions. Rather than following a questionnaire, the guide of interview consisted of open-ended questions supplemented with examples of closed-ended questions only used to rephrase or clarify the discussion (Table 5.1). Interviews were noted but not tape recorded. There was no pre-determined order in these discussions and we did not insist to absolutely obtain an answer to each of our questions, so as to follow the participant's train of thought. This flexibility offered the opportunity to skippers to talk about subjects that had not been previously identified as important by fisheries scientists. This also resulted in varying numbers of answers for each question (not all the 14 skippers answered each question of the interview guide) and varying length of the interviews (from 1 to 4 hours). As a consequence, a simple count of the occurrence of keywords identified in skippers' answers was used to rank their relative importance.

Table 5.1: Structure of the interview guide during phase 1 (detailed version in Appendix D1)

Theme	Sub-theme	Question
1. modalities in FOB use	a) deployment	deployment factors
	b) monitoring	number of FOBs, dFADs/natural FOBs, French/Spanish FOBs
	c) fishing	searching activities, preference for FOB or Free Swimming Schools, size of fishing sets
2. changes for FOB fisheries	a) technological and strategic changes	changes in catches, seasons and zones, importance of echosounder buoys
	b) management tools	IOTC time-area closure, Chagos MPA, Somali EEZ

Among others, these interviews underlined the importance of lost FOBs (analyzed in Maufroy et al., 2015 chapter 1), described the strategies of FOB deployment by purse seiners (analyzed in Maufroy et al., 2017 chapter 2), suggested a strong increase in the use of dFADs and GPS buoys (analyzed in Maufroy et al., 2017 - chapter 2) and an impossible separation of fishing effort between Free Swimming Schools (FSC) and FOBs, a long pending and yet unresolved issue (Maufroy et al., in prep - chapter 3).

Table 5.2: examples of results of phase 1 and their use to guide statistical analyses. Various hypotheses had been formulated before the interviews (assumption). They were confronted to skippers knowledge for validation or reformulation (information from interviews) and used to guide statistical analyses (results of the thesis).

Theme	Assumption	Information from interviews	Results of the thesis
Deployment of FOBs	Seasonality of deployments	Importance of seasons Importance of currents	Four seasons, Seasonal patterns of drift
	All dFADs are not used	- Stolen GPS buoys - FOBs lost with currents	10% beaching “ghost” fishing effort
FOB population	Separation between: - natural FOBs / dFADS - dFAD vs log zones - French / Spanish buoys	- Mozambique Channel vs Somalia - Spanish: more buoys	Separation of FOBs - per type - per fleet to estimate the use of FOBs
FOB fishing	Separation of FOB /FSC possible to measure fishing effort	Two types of searching activities conducted at the same time	Measure of efficiency combining the two types of schools

5.4. Phase 2: confronting quantitative analyses to fishers perception

5.4.1. Preparation of the interviews during phase 2

During the first phase of the study, LEK had been used to improve scientific knowledge of functioning and consequences of FOB fisheries. From August to September 2015, the results of the ongoing research conducted on FOB use (i.e. results from chapters 1 and 2) were presented to 15 French skippers arriving in the port of Victoria (among which 6 had participated in the interviews in 2013). The objective of this second phase was to confront the knowledge derived from quantitative data to fishers’ perception of the impacts and the existing management of the fishery, in order to propose adapted management tools

Table 5.3: Structure of the interview guide during phase 2 (detailed version in Appendix D2)

Theme	Sub-theme	Question
1. modalities in FOB use	a) deployment	seasons, currents
	b) number of dFADs	increase in dFAD use, recent changes in strategies
2. consequences of dFAD use	a) tuna catch	catch, yield of fishing sets
	b) other species	bycatch, ghost fishing
	c) ecosystems	lost GPS buoys, dFAD beaching, ecological trap
3. management tools	a) existing management	seasonal closures, 550 GPS active buoys/vessel
	b) options for management	limitation of dFADs / GPS buoys, catch quotas, support vessels

In addition, two years after the first interviews, important changes had occurred for FOB fisheries of the Indian Ocean. Since 2014, pressure for the management of FOB fishing had increased with NGO anti-FOB campaigns. In 2015, important decisions had been made to limit the number of active GPS buoys to 550 per purse seiner in the Indian Ocean (Res 15-08) At the same time, French fishing companies that had restricted their use of GPS buoys to 200 per year and per vessel since 2007, finally decided to increase this limitation to 400-500 . The opinion of skippers on these changes was also solicited. As in 2013, the occurrence of families of keywords was used to rank their relative importance. Interviews lasted from 2 hours to 4 hours and once again, our objective was not to obtain an answer to each question of the interview guide, but to understand which of these questions were important to skippers. Therefore, not all skippers answered each question, and some skippers provided several answers to the same question (i.e. the number of answers does not necessarily sum to 15). When this was possible, answers provided in 2013 where compared to answers provided in 2015.

5.4.2 Results

5.4.2.1 Recent changes in the use of FOBs in the Indian Ocean

Why is the use of FOBs increasing in the Indian Ocean?

French skippers confirmed the increasing use of FOBs by French fishing purse seiners identified by Maufroy et al. (2017– chapter 2). Although 69.2% of interviewed skippers were not in favour of the recent decision of French fishing companies to increase their use of GPS buoys, 80% of them also considered that they did not have any alternative. 12 skippers on 15 thought this was necessary to compensate for an increased competition with Spanish purse seiners using more FOBs and benefiting from support vessels (Figure 5.2). Then came considerations on potential improvement of their catches (7 skippers), compensation for GPS buoys lost outside fishing grounds or FOBs appropriated by other fishing vessels (6 skippers), relative inefficiency of fishing on FSC compared to FOB fishing (5 skippers) and the virtual absence of management of FOBs (4 skippers).

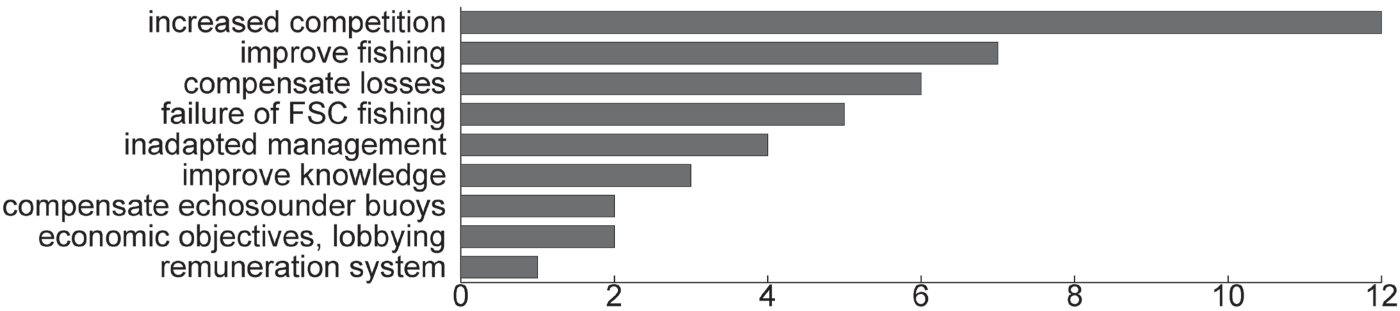


Figure 5.2: reasons to increase the use of FOBs by French purse seiners in the Indian Ocean

Does the increasing number of dFADs modify skipper's strategies?

In 2013 and in 2015, skippers indicated that their knowledge on the appropriate zones and seasons was the main factor used to deploy their dFADs and GPS buoys (Figure 5.3). Though there were only two years between the two groups of interviews, some skippers interviewed in 2013 indicated in 2015 that the increasing availability of GPS buoys had slightly changed their deployment strategies. With more GPS buoys, it would be possible to maintain a relatively dense array of FOBs. Answers provided by skippers that were interviewed in 2015 only confirmed these changes, as more skippers indicated that the density of FOBs within the area was an important factor to deploy new dFADs and GPS buoys. Also, more skippers took advantage of periods without fishing to deploy dFADs and GPS buoys.

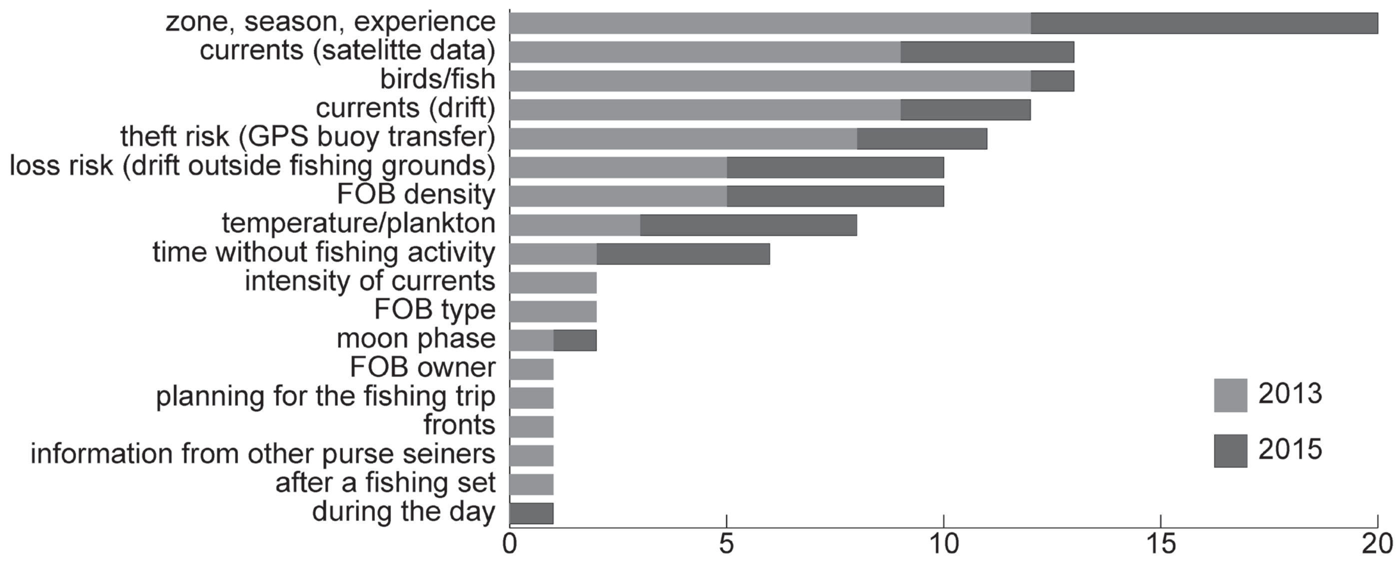


Figure 5.3: factors to decide on deployment of a new dFAD or a new GPS buoy

5.4.2.2. Skippers' perception of the impacts of FOBs on tropical tunas

Do FOBs alter the natural behaviour of tropical tunas ?

Among the potential effects of FOBs, assumptions regarding the alteration tuna behaviour were discussed with skippers (Figure 5.4). First, the idea that the increasing use of dFADs may contribute to an ecological trap (Marsac et al., 2000; Hallier and Gaertner, 2008), by trapping tunas in suboptimal zones, where their condition factors decrease (Ménard et al., 2000) and their natural feeding migrations are altered (Marsac et al., 2000) was proposed to skippers. On the 11 skippers who answered this question directly, 7 rejected this assumption, 2 of them thinking that this would only be valid in the Atlantic Ocean where they had experienced this situation. However, 7 skippers indicated that Free Swimming Schools of tunas were progressively disappearing, while 5 of them indicated that tuna migrations seemed altered, at least on short time scales.

Second, the potential fragmentation of tuna schools between FOBs was discussed (Sempo et al., 2013). Half of the skippers agreed that the situation existed or could exist while the other half rejected this possibility. On the contrary, most of them had observed a high proportion of FOBs without fish and a greater instability of schools that constantly moved from one FOB to the other, indicating possible shorter time of residence under FOBs. These discussions were principally based on decreasing trends of the catch per fishing set on FOBs since 2004. During these discussions, skippers also explained the apparent decrease in the size of schools in catch data by improving technological means allowing to detect smaller schools of tunas (7 skippers) and a diminution of the preferred minimal size of schools to set the net (9 skippers).

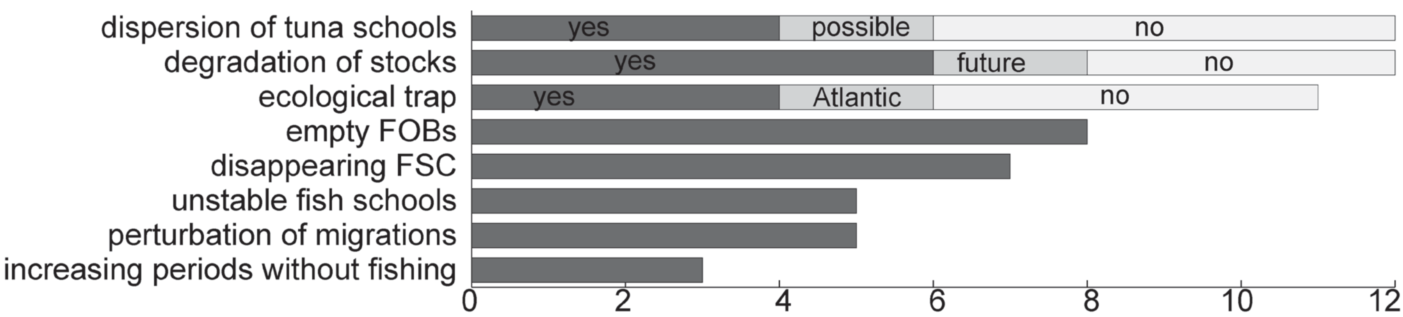


Figure 5.4: perception of skippers of FOBs impacts on tropical tunas

Can the increasing use of FOBs lead to overfishing?

In addition to these potential changes in the behaviour of tropical tunas, we simultaneously presented the evolution of catch per vessel and per year and the evolution of the number of French GPS buoys. French skippers had diverse points of view regarding the absence of increase in their annual catches following their increasing use of FOBs. Half of the skippers indicated a potential degradation of tropical tuna stocks, though their impressions were almost always related to relatively low catches during their last fishing trip. However, they provided other possible explanation such as the increasing competition with the efficient Spanish purse seine fleet (8 skippers on 15) and the increasing use of echosounder buoys that reduced the chances to find tuna under FOBs of other purse seiners.

5.4.2.3. Skippers' perception of the impacts of FOBs on marine ecosystems

How do skippers perceive the issues of bycatch and ghost fishing?

One of the major source of concerns regarding the impacts of FOBs is their contribution to higher levels of bycatch (Amandè et al., 2011, 2012) and ghost fishing of sharks and sea turtles (Anderson et al., 2009; Filmalter et al., 2013). Most skippers felt the need to justify themselves before any question was asked. During discussions on the problems of bycatch and ghost fishing, most skippers indicated that these issues were minor ones for the purse seine fishery (Table 5.4), due to relatively low volumes of bycatch (6 skippers), efforts to discard fish alive (4 skippers) and to use non-entangling dFADs (6 skippers).

They generally considered the landing obligation (that came into force in 2015) as irrelevant primarily because they had the impression that discarded fish could survive and re-attract tuna to the FOB (3 skippers considered that the survival rate was 90%, though they did not precise the origin of this estimate). Most of them also had the impression to have made significant effort, by discarding fish alive and using non-entangling dFADs that had visible effects on the frequency of sharks and turtles ghost fishing. Some of them also raised the issue of the trade of bycatch landed in Seychelles, due to the absence of local markets and to problems of conservation of small bycatch fishes onboard.

Table 5.4: perception of skippers of the impacts of FOBs on bycatch species

Theme	Sub-theme
Levels of bycatch	Very limited importance: 6 skippers Fish discarded alive : 4 skippers Uncertainty in the survival rate: 2 skippers Impact decreasing on sharks and turtles: 4 skippers
Discard ban	Irrelevant: 7 skippers / Relevant: 1 skipper The fish could have survived: 4 skippers Absence of market: 2 skippers Problem of conservation in fish wells: 1 skipper
Non entangling dFADs	Reduction of entanglements: 6 skippers Do not fully solve the problem of sharks: 2 skippers

How do skippers perceive the issue of FOB beaching?

Interviews of 2013 had underlined the importance of lost FOBs. Examination of quantitative data revealed that an important fraction of these lost FOBs would end up beaching. In 2015, skippers had differing points of view regarding the severity on the impacts of such beaching events, as approximately 1/3 of them considered that these impacts were low, 1/3 considerate they were moderate and 1/3 considered they were high (Figure 5.6). They thought that these beaching events could be problematic for ecosystems, through pollution (6 skippers) and degradation of coral reefs (5 skippers). But they also discussed about the economic consequences of such beaching events due to the cost of lost GPS buoys (3 skippers) and more importantly due to detrimental effects on tourism (6 skippers). Skippers identified the increasing use of dFADs (7 skippers), the design of dFADs with long underwater structures (3 skippers) and the difficult prediction of the trajectory of FOBs (3 skippers) as aggravating factors. The use of biodegradable non entangling dFAD (5 skippers), the reduction of the number of dFADs (7 skippers) and the use of a support vessel to retrieve lost FOBs (3 skippers) would help reducing the impacts of FOB beaching.

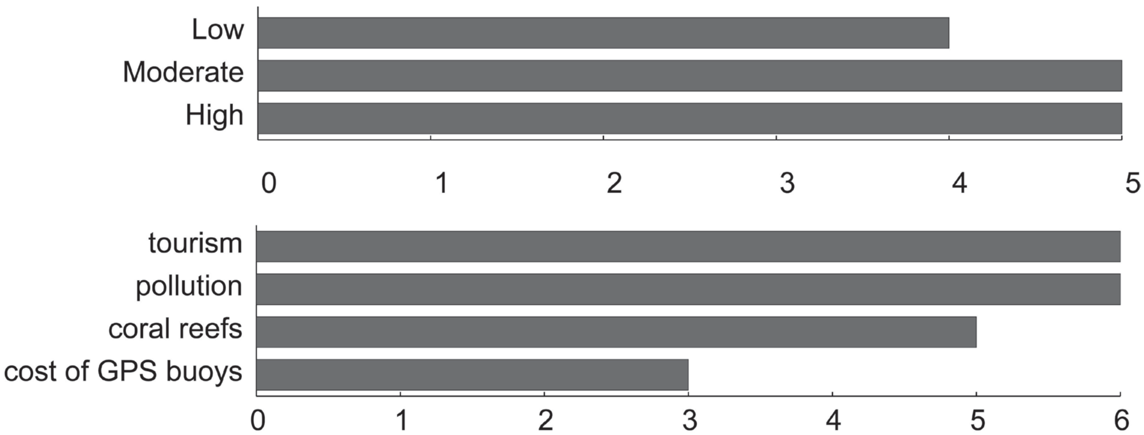


Figure 5.5: perception of skippers of FOBs impacts on tropical tunas

5.4.2.4 Fishers' perception of the management of FOB fisheries

Why should we manage FOB fisheries?

Throughout the interviews, skippers had the opportunity to express their opinion on the general management of the fishery, as well as on the management of some specific issues (see previous sections on bycatch and FOB fishing). 14 skippers felt there was a need to manage the fishery, primarily because they thought there were too many dFADs, GPS buoys, purse seiners and support vessels (Figure 5.6). Most skippers were concerned about the future of the fishery and their future catches and felt that management was virtually absent (7 skippers). However, their concerns were often not related to the state of tropical tuna stocks.

The virtual absence of management has created a strong resentment against other purse seine fleets. Many French skippers thought that other purse seine fleets were not obliged to follow the same rules as French skippers (9 skippers) and were even not complying with existing rules (10 skippers). Though similar regulations obviously apply to all EU purse seiners, this resentment may be explained by different factors. First, all French skippers indicated that other skippers benefited from better fishing tools with more GPS buoys and the assistance of support vessels. Therefore, they were more efficient and French skippers had the impression that there was an increased competition to get their share of catches. Second, there were increasing conflicts between French purse seiners and support vessels from other fleets, as 8 skippers thought support vessels would steal their GPS buoys even in time-area closures or in the Somali EEZ. Finally, French fishing companies had decided in 2012 to limit their use of GPS buoys to 200 per purse seiner and per year. This voluntary decision had not been followed by other purse seine fleets, leading to a further impression of inequity between the two fleets.

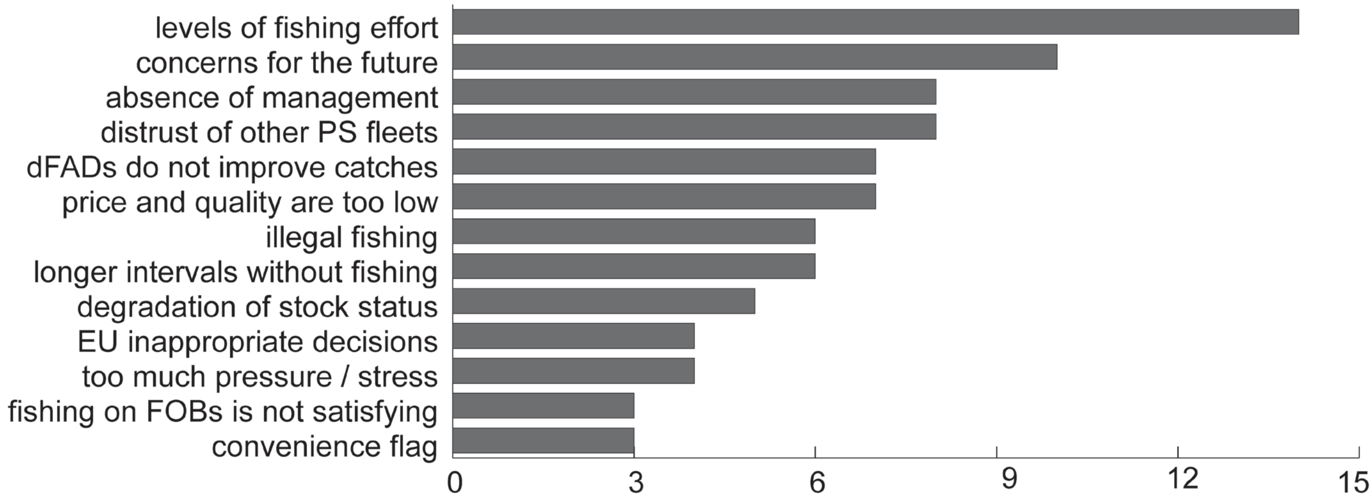


Figure 5.6: reasons to manage FOB fisheries in the Indian Ocean

Is a limitation to 550 GPS buoys an appropriate management tool?

13 of the 15 skippers agreed that regulating the use of dFADs and GPS buoys was necessary but none of them thought that the limitation of active GPS buoys could be effective (Figure 5.7). They felt that there was a high risk of non-compliance, primarily due to unclear definitions in IOTC Resolution 15-08 and issues in enforcement. They were not sure whether support vessels were included in the limitation (5 skippers) and wondered if purse seiners could hide a fraction of their GPS buoys by temporary deactivations (4 skippers). In order to be effective, additional regulations should be adopted, such as a limitation of the number of buoys purchased per year (3 skippers, measure already included in Res 15-08) or a reduction of the number of purse seiners (2 skippers) and support vessels should be included in the limitation (2 skippers).

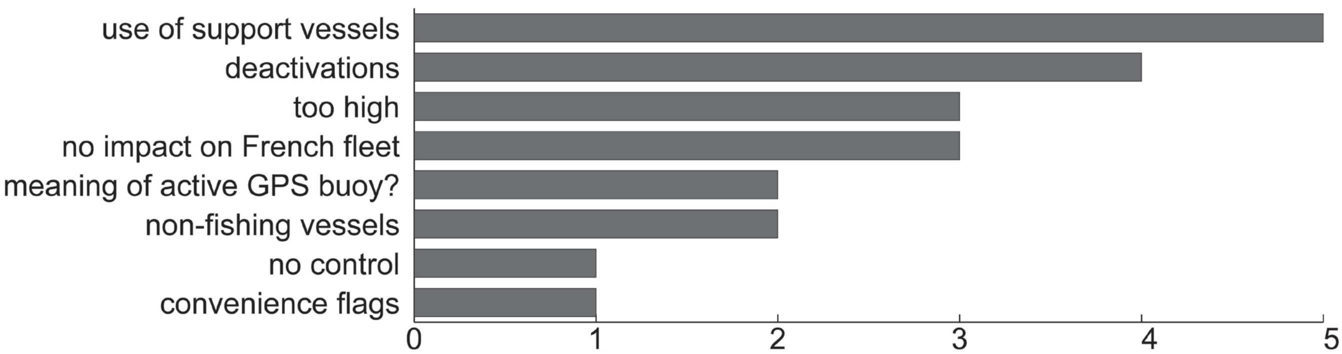


Figure 5.7: problems with the limitation of active GPS buoys in the Indian Ocean

Which management tools would be best adapted?

In addition to a limitation of the number of active GPS buoys, other management tools were discussed with skippers, to identify those that would be best adapted to the fishery and the conditions to make them efficient. Results are summarised in Figure 5.8 and Table 5.5. By order of importance, potential management included a regulation of fleet capacity, support vessels, a limitation of the number of GPS buoys see 5.3.4), catch quotas, and no-take zones. The potential for a ban of dFADs was also discussed but strongly rejected by skippers. They disagreed with the idea that dFADs are destructive fishing gears, and raised the importance of canned tuna. In addition, they highlighted the potential difficulties for purse seiners with a dominant FOB strategy, due to their potential lack of knowledge on FSC fishing or to the size of large purse seiners that mostly rely on FOBs to be profitable.

During the interviews, all skippers indicated that the fishery suffered of a problem of excess fishing effort and excess fishing capacity due to an excessive number of purse seiners (8 skippers) and their increasing size and capacity (6 skippers). They generally considered that this problem of capacity was somehow connected to the increasing use of dFADs, GPS and echosounder buoys, and support vessels. Though they agreed that decisions should be made to control fishing effort and capacity, they also indicated various conditions that would reduce the efficiency of fleet capacity limitations. First, several large purse seiners of the Eastern Pacific Ocean had recently left this ocean for the Indian Ocean, shifting the problem of capacity elsewhere. Second, the motivations of the governments of distant water fishing nations and coastal countries were questioned due to a possible race for fishing anteriority (in case catch quotas would be implemented, the objective would be to have more fishing vessels to have a larger share of TACs), EU subsidies and vessels flying flags of convenience.

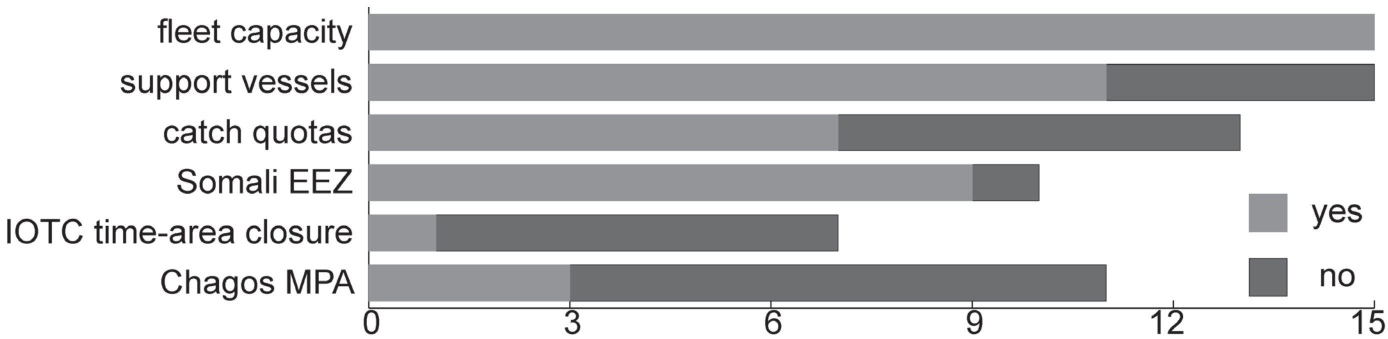


Figure 5.8: agreement of skippers with potential and existing management tools

Skippers also indicated that there were growing problems with the use of support vessels and 73% of them agreed to the suggestion that their use could be banned. Most of the time, they considered that there was an insufficient control of these vessels, and even doubted that they were included in the limitation of 550 GPS buoys per vessel (see section 5.3.4). In addition, they had observed high rates of “theft” of their GPS buoys in the Somali EEZ and in the IOTC moratorium (Figure 5.1) and attributed them to support vessels. However, French skippers also indicated that prohibiting the use of support vessels could have important consequences for large purse seiners that heavily rely on FOBs and indicated that French fishing companies had already decided to invest in support vessels.

Then, the question of catch quotas was discussed (Table 5.5). Half of the skippers considered that they were an appropriate management tool for the fishery, as they could increase tuna market prices, improve the state of tropical tuna stocks or rebalance fishing effort between purse seine fleets. This tool has also been successful in other fisheries and would mechanically reduce, among other gears, the number of purse seiners, support vessels and dFADs. On the other hand, 50% of French skippers considered that catch

Table 5.5: potential management of FOB fisheries. Pros include motivations to implement the tool (e.g. to reduce the number of fishing vessels) and the expected outcomes (e.g. regulate the use of GPS buoy). Cons include potential difficulties regarding the implementation of the tool (e.g. finding a consensus) and potential negative consequences (e.g. issues of profitability)

Management tool	Pros	Cons
Number, size, carrying capacity of purse seiners	• too many vessels : 8 skippers • too large vessels: 6 skippers • fuel consumption: 3 skippers • regulation of GPS buoys: 1 skipper • improve yield per vessel: 1 skipper	• vessels may leave for another ocean: 4 skippers • this creates a race for fishing anteriority: 2 skippers • flags of convenience: 2 skippers • EU subsidies: 1 skipper • economic consequences (investments made already): 1 skipper
Support vessels	• they do not comply with EEZs: 9 skippers • there is no regulation of support vessels: 7 skippers • they appropriate fish/FOBs: 4 skippers • this could regulate the use of GPS buoys: 3 skippers • they should be accounted for in the 550 buoys limitation: 2 skippers	• issues of profitability for large purse seiners: 2 skippers • support vessels could be used to limit beaching: 2 skippers • French companies will soon have support vessels too: 2 skippers
Catch quotas	• to regulate prices: 3 skippers • to improve stocks/yield: 2 skippers • some fishing companies do not consider the long term : 2 skippers • they may be easier to enforce: 1 skipper • they have proven successful in other fisheries: 1 skipper • this could regulate capacity, support vessels and FOB use: 1 skipper	• allocation criteria: 2 skippers • this creates a race for fishing anteriority: 2 skippers • difficult to choose between different fleets and their strategies: 2 skippers • obligation of regularity in catches (to avoid fast quota exhaustion): 2 skippers • problem of consensus: 1 skipper • ineffective if catches are not significantly reduced: 1 skipper
Spatial management (including no-take areas)	• spillover ("fishing the line"): 5 skippers • to protect GPS buoys against theft: 5 skippers • to protect juveniles: 3 skippers	• supply vessels do not comply: 5 skippers •inappropriate choice of period: 3 skippers • such management measures are only communication tools: 2 ski

quotas would not be an appropriate solution. They discussed about the problem of allocation criteria and consensus, race for fishing anteriority and economic difficulties for purse seiners with a dominant FOB strategy.

Finally, the question of spatial management of the fishery, that has been the main tool used so far in the Indian Ocean (Fonteneau and Chassot, 2014) provided different answers depending on the area that was considered. French skippers generally considered that the past IOTC no-take area of November and the Chagos Archipelago MPA had little impact on the fishery because of inappropriate choice of zones and seasons. Purse seiners generally leave the Somali fishing ground before November and target Free Swimming Schools in the vicinity of the Chagos Archipelago and in the Seychelles EEZ. On the contrary, though the Somali EEZ is not strictly speaking a fishery closure, skippers considered that the absence of fishing agreements to access this area (due to problems of piracy) could protect tuna juveniles. However, their interest in the zone was not only for the protection of juveniles, as they also indicated that they could hide their GPS buoy equipped FOBs in the area and wait for them on the border of the EEZ (in a typical “fishing the line” strategy, Kellner et al., 2007).

5.5 Discussion

In the present study, scientific and local ecological knowledge were treated as equally important to gather useful information on the FOB fisheries, understand the consequences of the increasing use of FOBs on tropical tuna stocks and marine ecosystems and finally to identify possible management tools of the fishery. Among others, results indicate that French skippers have different points of view regarding the impacts of the increasing use of FOBs on tropical tunas, bycatch species and vulnerable habitats (through beaching of lost dFADs). They generally indicated that the current management of the FOB fishery was either inappropriate (e.g. discard ban or limitation of active GPS buoys) or inexistent (e.g. number and size of purse seiners). Potential for new management decisions was raised, including managing the capacity of the purse seine fleet, regulating the use of support vessels, implementing catch quotas and addressing other important issues such as illegal fishing.

5.5.1 Skippers perception of the impacts of the fishery

In 2015, French skippers were seemingly less concerned with the impacts of FOBs for bycatch species and marine ecosystems than for tropical tunas. They generally indicated that the issue of bycatch was a minor one while the issue of lost FOBs was partly a problem of image if dFADs ended up beaching in touristic areas such as the Seychelles and the Maldives. The perception that the use of FOBs is causing only minor collateral damages on marine ecosystems is not surprising. Though FOB fishing induces higher levels of bycatch than fishing on Free Swimming Schools (Amandè et al., 2011, 2012), levels of bycatch remain relatively low for purse seiners compared to other fishing gears such as pelagic longlines or gillnets (Gilman, 2011). Besides, purse seine skippers often pointed out the efforts made to mitigate bycatch such as the presence onboard of scientific observers or cameras (increasing in 2015 to reach 100%) and the development of non-entangling dFADs that reduced ghost fishing of sharks and sea turtles (Franco et al., 2012; Hernandez-Garcia et al., 2014). However, purse seine skippers may also have minimized the effects of FOBs on bycatch due to the growing pressure of NGOs who are using this argument to advocate for a reduction or a ban of dFAD use (e.g. http://www.greenpeace.org/france/fr/campagnes/oceans/arrethon/). Finally, their point of view may also be related to the recent implementation of a tuna discard ban by the IOTC (Res 13-11) that was inducing additional constraints for purse seiners. Nevertheless, although French skippers often disagreed with the idea that bycatch is a serious issue of FOB fisheries, concerns regarding catches of yellowfin and bigeye tuna, as well as impacts on sensitive shark species remain important.

French skippers raised various concerns for tropical tuna stocks, that they considered as more serious than concerns for non-target species. Though 50% of them indicated that tropical tuna stocks could suffer from overfishing, their concerns were more related to important changes in the behavior of tropical tuna schools. They had different points of view regarding the potential of an ecological trap due to the increased use of dFADs (Hallier and Gaertner, 2008; Marsac et al., 2000) but described other phenomena: the dispersion of schools (as suggested by Sempo et al. 2013) a progressive disappearing of Free Swimming schools (the steady decline of skipjack free schools since 1991 in the Atlantic and since 1994 in the Indian Ocean, has been described in (Fonteneau, 2015; Fonteneau et al., 2000b), Fonteneau 2014) or an instability of schools under FOBs. These suggestions could guide new research on the behaviour of tropical tunas at FOBs, for example using simulations and data from echosounder buoys used by purse seiners. However, in the absence of quantification of the potential changes in the behaviour of tunas, skippers mostly relied on their personal opinions and scientific analyses are required to verify their suggestions.

Even though 50% of purse seine skippers did not have the impression that the use of FOBs would lead to overfishing, these results suggest at least that a too important use of FOBs may not be optimal. From an economic point of view, if increased densities of FOBs reduce their attraction potential (due to the dispersion and the instability of schools), deploying large number of dFADs may have a counterproductive effect. Besides, if too large numbers of GPS and echosounder buoy-equipped FOBs are in use, conflicts may arise between purse seine fleets, due to an increasing competition to get the larger share of catches.

5.5.2 The tragedy of the commons: once again?

During the interviews of 2013 and 2015, purse seine skippers pointed out a general problem of overcapacity. This problem is not a new one for tropical tuna fisheries and has been discussed since the end of the 1990s at least (Greboval and Munro, 1999; Morón, 2007; Reid et al., 2005). In 2015, excess fishing capacity was related to an absence of direct regulation of the capacity of the fleet (number, size and carrying capacity of purse seiners) but also an absence of indirect regulation, through a control of support vessels and a monitoring of FOB use. This virtual absence of efficient regulation seems to have created a generalized race-to-fish. This situation, well known in open access fisheries as the ‘Tragedy of the commons” (Hardin, 1968) may have encouraged over-investment during the last decade. At first, the increasing number of dFADs and GPS buoys (Maufroy et al. 2017 – chapter 2) contributed to an increase in the size of purse seiners, as building larger vessels had become profitable (Le Gall, 2000, Maufroy et al. in preparation– chapter 3). But at the same time, these large purse seiners became dependent on their FOBs and support vessels and induced a competition with French purse seiners who did not benefit from equivalent FOB fishing tools.

For some time, French fishing companies decided to set an auto-limitation of their use of GPS buoys

(200 per vessel and per year). This was rather an unexpected decision in the absence of regulation. In this typical case of "Tragedy of the Commons" (Hardin, 1968) each fishing company should normally choose to increase its use of FOBs to increase catches on the short term, regardless of the consequences for tropical tuna stocks on the long term. In theory, this could only last if each French fishing company agreed to comply with this decision, even if this could reduce potential catches (though the value of FSC catches is higher, Guillotreau et al., 2011). In 2015, French skippers explained that this was not the case anymore. The decision of the IOTC to limit the number of GPS buoys per vessel even had an unexpected effect. As this number was rather high (550 GPS buoys per day i.e. 5 times more than the 100 GPS buoys per day used by French purse seiners, Maufroy et al. 2017 – chapter 2), instead of reducing the general use of FOBs, this contributed to an increase in the use of GPS buoys by French purse seiners. French skippers explained that they had no other choice due to the competition with other purse seine fleets. This situation indicates that a sole management of the use of FOBs may not be efficient, if other components of fishing efficiency and fishing capacity are not regulated.

5.5.3 Other solutions: regulating fleet capacity and implementing quotas

In addition to a regulation of FOB use, other management tools may be adapted by the fishery. Ideally, as underlined by several skippers, these tools should be as simple as possible and should be easy to implement. Due to their limited effects, no-take zones, FOB moratoria and discard bans may be eliminated directly from this list (Fonteneau et al., 2015; Fonteneau and Chassot, 2014). A ban of dFAD deployment or FOB fishing suggested by environmental NGOs may not be an appropriate solution either (Davies et al., 2015) for obvious socio-economic reasons. Other solutions would therefore be: (i) a regulation on the use of support vessels (ii) a regulation on the fleet capacity for all gears (leading inter alia to a reduction of the number of purse seiners) (iii) a regulation on catches through catch quotas.

According to skippers, all these potential solutions are connected to each other (Figure 5.9). Among potential tools for the management of the fishery, the implementation of catch quotas may seem promising management tools, though only 50% of French skippers were favourable to this type of management. Catch quotas would indeed reduce the interest of having large numbers of purse seiners using large numbers of dFADs and GPS buoys, in collaboration with support vessels. This regulation could be relatively easy to enforce by controlling landings of purse seiners, but this would not solve the problems of under-estimation of artisanal catches or the problem of IUU fishing. Also, IOTC past attempts to implement such quotas have failed, as finding a consensus is difficult.

An alternative would be to limit the number of purse seiners and their size. On the contrary to catch quotas, 100% of interviewed French skippers were favourable to a reduction of fishing effort and fishing capacity. This tool would only effective it the decision was made on a global basis to avoid displacing the problem in other oceans. This would also imply addressing issues of reflagging (Birnie, 1993), subsidies (Le Manach et al., 2013; Sumaila et al., 2010) and IUU fishing (Agnew et al., 2009) that were all identified by French purse seine skippers. Finally this would require having fine scale information on the use of GPS buoys and support vessels, as they greatly contribute to fishing efficiency (Maufroy et al. in preparation – chapter 3) and therefore encourage overcapacity in purse seine fisheries.

To conclude, there was a general consensus of French purse seine skippers that the fishery needed a more appropriate management. Fisheries scientists and environmental NGOs have also called for a better management of FOB fisheries in the Indian Ocean sometimes more than a decade ago (Fonteneau 2003). Integrating scientific knowledge and LEK like in this study seems a promising tool to prioritize and identify potential management solutions. In the future, similar studies implying more stakeholders of the fishery (NGOs, tuna cannery, fishing companies and managers) in each ocean could be used to achieve a successful Ecosystem Approach to Fisheries.

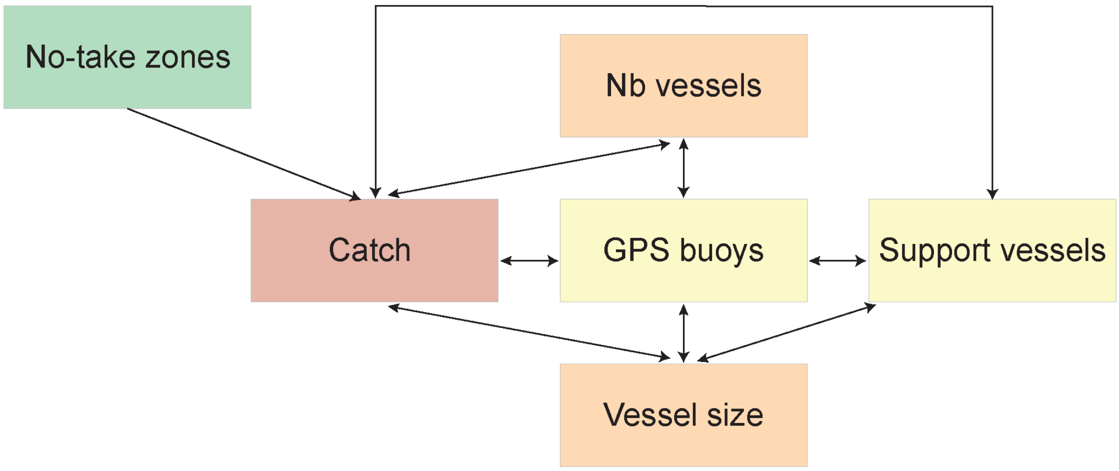


Figure 5.9: potential management tools for FOB fisheries. Arrows indicate the interactions between different management solutions and colours indicate the level of restriction

Appendix D1: Interview guide used in 2013

Thème	Sous-thème	Question à poser
Renseignements sur le patron	*Niveau d'expérience*	1. Quel a été ton parcours jusqu'à aujourd'hui ? a) depuis combien de temps est-tu patron ? b) depuis combien de temps sur ce bateau ? c) as-tu aussi travaillé dans l'Atlantique ? d) as-tu aussi travaillé pour un armement espagnol ?
Activités type à bord	*Déroulement d'une marée*	2. Comment se passe une marée type à bord ? en t'appuyant sur des zones/saisons ? a) combien de temps dure une marée ? b) quelles sont les quantités pêchées ? c) comment les activités changent-elles selon la saison et la zone ? d) quel temps est dédié à la recherche, à la pêche, BL vs BO ? e) collabores-tu avec d'autres bateaux ? (supply, sistership, autre)
Modalités d'utilisation des DCP	*Mise à l'eau des DCP et balises*	3. Pour toi, qu'est-ce que c'est un DCP ? 4. Comment utilises-tu les radeaux et les balises ? lien avec toutes les questions suivantes 5. Que se passe-t-il au moment de la mise à l'eau d'un radeau ou d'une balise ? lien vers question 6 a) Quelles sont les étapes dans la mise à l'eau ? (avant, pendant, après) b) combien de temps ? à quelle heure ? c) sur 100 objets naturels rencontrés, combien en balises-tu ? d) idem pour les renforcements e) que se passe-t-il lorsque tu rencontres un objet déjà balisé qui pourrait t'intéresser plus tard ? f) sur 100 objets et radeaux balisés par d'autres bateaux, combien de transferts de balise réalises- tu ? pourquoi ? 6. Quand et comment prépares-tu une mise à l'eau ? lien vers questions 7,8,9 a) à quelle heure ? b) de quoi dépend cette décision ? (ce que tu observes autour, un planning pour la marée, une information, une consigne de l'armement) c) qu'est-ce qui rend une zone intéressante pour une mise à l'eau ? (densités d'objets dans la zone, de balises dans la zone, autres bateaux dans la zone, agrégations sous l'objet déjà à l'eau, conditions de courant, présence d'oiseaux et de poissons, fleuves …) d) quelles sont les différences entre zones et saisons ? e) au total, combien de radeaux et de balises mets-tu à l'eau ? f) (selon parcours) d'après ce que tu connais/ton expérience, différences avec les autres flottes ? g) (selon son parcours) d'après ce que tu connais/ton expérience, des différences dans l'Atlantique ? 7. Quand les radeaux sont-ils préparés et les balises allumées pour être mis à l'eau ? a) Si la mise à l'eau ne suit pas directement la préparation, pourquoi ? b) Pendant combien de temps à bord avant la mise à l'eau ? c) (expliquer le principe de la classification) j'ai obtenu ces cartes de déploiement, qu'en penses-tu ? sont-elles cohérentes avec tes activités et tes observations ?

Thème	Sous-thème	Question à poser
Modalités d'utilisation des DCP	*Trajectoires des DCP*	8. Après mise à l'eau des balises/radeaux, quelles sont les étapes jusqu'à la pêche / récupération ? lien vers question 9
		a) La trajectoire d'un radeau/balise est-elle prévisible ? pourquoi ? b) Sur quoi te bases-tu pour la prévoir ? (données en temps réel de courant, dérive d'un groupe de balises, expérience, informations d'autres bateaux) lien vers question 11 c) Utilises-tu les courants pour planifier la dérive ? si oui, comment ? (échelle locale ou grands courants, comparaison trajectoire prévue et réalisée, etc) d) Combien de temps laisse-tu un radeau ou une balise en mer en général ? (min-max) e) Est-ce que ce temps varie selon le type d'objet, de balise, la zone, la saison ? lien vers question 11
	Recherche des bancs	9. Sur BL comme BO, comment prépares-tu les activités de pêche ? lien vers question 6, 7, 8, 10, 11
		a) comment se fait la recherche des bancs? lien vers questions 10, 11 b) quand décides-tu de changer de cap ? c) comment est prise la décision de se rendre sur une balise ? d) quand tu cherches une balise, tu continues de regarder les BL et objets non balisés par toi? e) Quand tu cherches des BL, est-ce que tu continues de t'occuper de tes balises dans la zone ? f) quand tu as décidé de visiter une balise, dans combien de cas (sur 100) dévies-tu ta route pour : un autre objet, un BL ? g) ces proportions changent-elles avec les bouées échosondeurs ? (ie peux-tu te permettre d'attendre quand tu sais qu'il y a du poisson sous un objet ?) h) idem question f, en recherche de BL, pour un objet balisé par toi ou un autre type d'objet ?
		10. De quelles informations disposes-tu pour visiter un objet et préparer un coup depêche ? Comment s'organisent les activités de recherche ?
		a) de quels instruments te sers-tu pour chercher des BL ? portée et précision ? b) idem pour les BO c) suis-tu toutes tes balises ou ne tiens tu compte que de certaines ? lesquelles ? combien ? d) y a-t-il selon toi des différences entre les flottes et l'IO vs AO ? e) échanges-tu de l'information avec d'autres bateaux ? qui et quoi ? supply ? f) quelle proportion des DCP partagés entre plusieurs bateaux ? lequel des « propriétaires » pêche ? g) si le bateau pêche avec d'autres : même armement ? même flotte ? raisons personnelles ? h) rôle de l'armement ? y a-t-il des consignes de pêche de sa part ?
	Pêche sur BL et BO	11. Quand tu as détecté un banc ou trouvé un objet, quand décides-tu de pêcher ?
		a) Qu'est-ce qui rend un objet ou un banc intéressant ? (quelle quantité, autre) b) Attends-tu avant de pêcher ? quand ? c) Pour un radeau, y a-t-il un lien entre temps de dérive et quantité ? composition des captures ? d) Pour les radeaux rencontrés, proportions suivantes : Balise/Sans balise /Appartient/N'appartient pas/DCP/naturel e) Quelles sont les différences entre zones et saisons ? f) Combien de fois mets-tu une balise à l'eau et pêches-tu dessus ? La récupères-tu sans pêche ? g) La perds-tu ?

Thème	Sous-thème	Question à poser
Changements	*Technologie et Outils de gestion*	13. Y a-t-il eu des changements dans l'utilisation des DCP ?
		a) De quelle nature et quelle ampleur ? f) vont-ils durer dans le temps ? b) Y a-t-il eu un changement dans la quantité capturée ? c) Dans les captures accessoires ? d) Dans les zones et saisons d'activité ? e) Dans la répartition BL/BO ? f) Dans les stratégies de mise à l'eau / pêche/ récupération ? g) Plutôt positif ou négatif ? h) Picolo, Chagos, Somalie : Influence de la période choisie ? i) respect de la mesure par les autres flottes ? j) possibilité de contourner la mesure par l'usage des DCP ? quelle participation des armements et des pêcheurs à la prise de décision ?

Appendix D2: Interview guide used in 2015

Thème	Sous-Thème	Question	Support
Présentation	*Renseignements sur le patron*	**1. Quel a été ton parcours jusqu'à aujourd'hui ?**	
		a) depuis combien de temps est-tu patron ? b) depuis combien de temps sur ce bateau ? c) as-tu aussi travaillé dans l'Atlantique ? d) as-tu travaillé pour un autre armement ?	
Utilisation des balises GPS et des DCP	*Mise à l'eau des balises GPS et des DCP*	**2. Comment utilises-tu les radeaux et les balises GPS ?** → 3	
		a) comment décides-tu de les mettre à l'eau ?	
		b) En 2013, j'avais posé cette même question à 14 patrons, que penses-tu de ces résultats ?	Figure 1 : réponses des patrons en 2013
		c) Dans leurs réponses, le choix de la zone/saison semblait être la raison principale pour décider de mettre à l'eau un nouveau radeau/une nouvelle balise. Les saisons identifiées te paraissent-elles cohérentes ? Différences avec tes mises à l'eau/ ce que tu connais des autres patrons/ flottes ?	Figure 2 : saisons de mise à l'eau (chapitre 2)
		d) L'utilisation des courants était en deuxième position dans les réponses des patrons. A l'échelle de la saison, la direction prise par les épaves et la vitesse te paraissent-elles cohérentes ?	Figure 3 : courants saisonniers (chapitre 2)
		e) Les zones et les saisons de mise à l'eau sont identiques aux zones et aux saisons de pêche. A quoi cela peut-il être dû ? p.ex fréquence des transferts.	Figure 4 : zones et saisons de pêche
		3. Combien y a-t-il de radeaux et d'épaves équipées de balises chaque jour dans l'Océan Indien? années, zones et saisons	
		a) les entretiens précédents et nos résultats suggèrent qu'il y a eu une forte augmentation du nombre de DCP et d'épaves balisées depuis au moins 2007. Es-tu d'accord avec ce constat ?	
		b) Entre 2007 et 2013, de 20 à 80 balises par jour et par senneur Français. Ces chiffres paraissent-ils cohérents ? (avec ton utilisation / avec ce que tu connais des autres patrons)	Figures 5 et 6: nombre de DCP des français, nombre de DCP total
		c) Entre 2007 et 2013, de 1500 à 1000 DCP par jour dans l'Océan Indien. Ces chiffres te paraissent-ils cohérents ?	
		d) Fin 2014, la Commission Thonière de l'Océan Indien a fixé une limite à 550 DCP par bateau. Quel est ton avis sur cette décision ? Trop restrictif/ pas assez ? Quelles conséquences ?	
		e) Les armements français ont prévu d'augmenter leurs balises. Quel est ton avis sur cette décision ? Pour quelle raisons penses-tu qu'elle a été prise ? Conséquences ?	

Thème	Sous-Thème	Question	Support
Gestion des impacts de la pêche sous DCP	*Conséquences de l'augmentation récente du nombre de DCP et de balises*	**3. L'augmentation du nombre de DCP est rapide et forte ces dernières années. Elle pourrait se poursuivre à un rythme important dans les années à venir (voir questions 2d à 2e)** **Quelles conséquences ont/pourraient avoir ces changements (positifs ou négatifs) ?**	
		a) les DCP augmentent mais pas les tonnages des Français, comment l'expliquer ? b) Une équipe de chercheurs a montré que lorsqu'on dépasse un certain nombre de DCP, au lieu d'avoir un gros banc sous un DCP unique, on risquait au contraire d'avoir de nombreux bancs sous de nombreux DCP. Que penses-tu de cette hypothèse ? c) as-tu observé des changements dans la taille des bancs ? d) Pêches-tu (volontairement) de plus petits bancs qu'avant ? e) en 2013, les patrons avaient évoqué leurs pertes de balises avec les courants. Les données permettent d'estimer que 10% des DCP s'échouent et que le nombre de DCP (total) augmente avec le temps. Observes-tu les mêmes tendances au cours du temps ? f) Quelles conséquences pourraient avoir ces pertes et ces échouages ? Est-ce important selon toi (d'en tenir compte, de le gérer) ou les impacts sont-ils négligeables (tout court ou par rapport à d'autres impacts plus importants)	Figure 7 : tonnages annuels Figures 7, 8: effort fantôme et échouages
		4. Il y a aujourd'hui beaucoup de discussions autour de l'utilisation des DCP et ses impacts. Quel est ton avis sur ces discussions ?	
		a) Y a-t-il un risque pour l'état des stocks de thons tropicaux ? Notamment, est-ce que les moyens mis en œuvre pour exploiter ces stocks te semblent modérés / nécessaires / trop importants ? b) Penses-tu qu'il y ait un risque d'augmenter les captures accessoires ? Ou d'augmenter les pêches fantômes de requins soyeux ? (DCP non éco) c) Les DCP modifient l'habitat naturel des thons et pourraient contribuer à une situation de piège écologique (migrations, alimentation, reproduction, etc). As-tu observé des changements qui vont dans le sens de cette hypothèse ? Qu'en penses-tu ? e) Ces impacts te semblent-ils faibles/modérés/importants/trop importants ? f) Y a-t-il d'autres impacts/phénomènes à prendre en compte dans cette réflexion ? Comment les prendre en compte ?	

Thème	Sous-Thème	Question	Support
Gestion des DCP	*Potentialités de gestion*	**5. Quels seraient les solutions adaptées pour gérer ces impacts ?** a) limiter le nombre de DCP b) limiter le nombre de balises c) limiter les navires supply d) utiliser des zones de fermeture saisonnières (mise à l'eau, utilisation ou pêche sous DCP) e) interdire certaines zones (mise à l'eau, utilisation ou pêche sous DCP) f) autres ?	

GENERAL DISCUSSION

6. General discussion

6.1 Overview of the thesis

During the last decades, global issues of overfishing and overcapacity have arisen (Caddy and Seijo, 2005; Cullis-Suzuki and Pauly, 2010). Tropical tuna purse seine fisheries are no exception to this recent history. In recent years, these fisheries have been increasingly criticised about the impacts and the management of their numerous FOBs (Fonteneau and Chassot, 2014), and crucial information is still lacking to manage FOB fisheries. The objectives of the present research were therefore to improve our knowledge of tropical tuna purse seine fisheries of the Atlantic and Indian oceans through a better understanding of the modalities of FOB use and their consequences. Throughout this dissertation, we aimed at providing answers to the issues faced by tuna RFMOs regarding FOB fisheries. In particular, how many dFADs and GPS buoys are currently in use in the Atlantic and Indian oceans? Where, when and how are they deployed? How does this affect fishing strategies and ultimately purse seine fishing efficiency? Could the increasing use of dFADs induce too important modifications of the pelagic habitat or impact vulnerable coastal habitats? And finally, how can we reconcile the point of view of different stakeholders of the fishery to improve its management? Principal findings of our research are discussed here along with the lines of potential work that this thesis has left open.

This research started when French fishing companies provided for the first time the positions of their GPS buoy-equipped FOBs. After much scientific work from the point of view of fish, these data provided a new opportunity to better understand the fishery from the point of view of fishers. When this research started, this was already much needed, as the fishery was again entering a phase a dramatic changes (described in chapter 2). Four years later, pressures for the management of the FOB fishery have considerably grown (discussed in chapter 4), together with concerns for tropical tuna stocks status. All along this dissertation, we have argued that detailed GPS buoy positions of all purse seine fleets would considerably improve the monitoring of the modalities in FOB use and their consequences. Chapter 1 provides a methodology for a routine treatment of such data when they become available. In chapters 1 and 2, “at sea” sections of GPS buoy trajectories are used to fill in knowledge gaps on the strategies of dFAD and GPS buoy use. Seasons and zones of deployment are identified, seasonal use of oceanic currents is described, numbers of GPS buoy-equipped FOBs are estimated (chapter 2) and time and distance at sea are measured (chapter 1). These chapters provided partial answers regarding some of the impacts of FOBs such as the beaching of lost dFADs (chapter 1) and the progressive artificialisation of the FOB population due to increasing numbers of dFADs (chapter 2). Chapter 3 meant to improve these initial reflections on the consequences of FOB use. The contributions of fishing strategies with FOBs and use of support vessels to the fishing efficiency of tropical tuna purse seiners were estimated. Fishing efficiency was decomposed into a technical efficiency explicitly considering support vessels and a strategic efficiency taking into account the relative use of FOBs and FSC. Throughout these analyses, some questions needed crossing point of views between science and other forms of knowledge. Interviews with purse seine skippers guided our analyses of chapters 2 and 3, confirming among others the necessary examination of the increasing use of FOBs. In chapter 4, LEK of fishers was gathered to propose adapted management tools of the fishery, such as catch quotas, fleet capacity regulations or control of support vessels.

6.2. Main contributions and limitations

6.2.1 Combining multiple sources of information to understand FOB fisheries

A large variety of sources of information were available for the present study (Table 6.1). This vast amount of data originated from French and Spanish purse seiners, the two main European fleets targeting tropical tunas with FOBs in the Atlantic and Indian Oceans. Logbook, VMS, observer, support vessel and GPS buoy data provided complementary but not always overlapping information, due to partial coverage (e.g. when data was only available for the French fleet) and differences in spatio-temporal scales (e.g. GPS buoy data was provided on a varying time scale). In addition, each of these data had been collected for a different purpose and described different types of activities with FOBs (e.g. observer data provided information on all types of activities on FOBs while logbook data only provided information on fishing sets). Finally, some of these data, such as logbooks, had been collected by French and Spanish institutes (IRD, and IEO) since the 1990s in the Atlantic Ocean and the 1980s in the Indian Ocean. They have been extensively used and validated for stock assessment (Chassot et al., 2015a, 2015b). Other sources of information such as observer data had been used for other purposes, such as an estimation of levels of bycatch (e.g. Amandè et al., 2011, 2012) or the identification of the positions of fishing sets (Bez et al., 2011). Yet, information collected by observers on activities with FOBs had rarely been used in detail (except in Dagorn et al., 2013). Finally, detailed GPS buoy position data were only available for the first time.

Therefore, the present thesis represents a significant effort to combine this large amount of fragmented and highly variable information on FOB purse seine fisheries (chapters 1 to 3). We not only combined various sources of information but also took into account different forms of knowledge, by placing a strong emphasis on crossing boundaries in available data as well as between stakeholders (chapters 2 to 4). Reconciling the sometimes conflicting points of view of fishers and fisheries scientists is not always an easy task (Johannes and Neis, 2007; Mackinson, 2001; Visser, 2004). Understanding social, economic and ecological aspects of fisheries (Fischer et al., 2015; Jentoft, 2006) is time consuming and adds a layer of complexity to already

Table 6.1: summary of information available for this study. Some of the sources of information were only available for the French fleet or for the Indian Ocean. They provided information of different nature (e.g. GPS buoy deployments or fishing sets on FOBs), on different spatio-temporal scales (1 minute to several years)

Source	Fleet / Ocean	Information	Precision	Chapters
GPS buoy data	French	positions of FOBs	1 h, 2 h, 1 d, 2 d	1 and 2
Logbook data	all EU	- position of fishing sets - catch - number of fishing sets - travelled distance	1 d, 1 m	1, 2 and 3
VMS data	French	positions of purse seiners	1 h	1
Observer data	all EU	activities on FOBs	1 min	2
Support vessels	Indian Ocean	collaboration between purse seiners and support vessels	1 y	3
LEK	Indian Ocean	- strategies in FOB use - consequences of FOB use - management options	several years	2,3 and 4

complex studies. Of course in our case, the integration of scientific knowledge and LEK certainly prevented a more in-depth examination of available quantitative data. Indeed, there are a number of additional questions that could have been addressed, with much more sophisticated approaches than those used in this thesis. For example, French FOB positions could have been used to understand how tropical tuna purse seiners allocate their fishing effort in time and space within a dynamic array of FOBs with appropriate models describing their VMS trajectories (e.g. Lévy flight, Markov Models). However, our pragmatic approach provides practical answers to the challenges of FOB fisheries, such as the first reliable estimate of FOB use in the Atlantic and Indian Oceans.

6.2.2 Improved understanding of the modalities of FOB use

The use of dFADs and GPS buoy-equipped FOBs has a number of potentially negative impacts: an increased pressure on tropical tuna stocks (Dagorn et al., 2013a; Fonteneau et al., 2013a), strong modifications of the natural behaviour of tunas (Hallier and Gaertner, 2008; Marsac et al., 2000; Sempo et al., 2013), increased levels of bycatch and discards compared to FSC fishing (Amandè et al., 2011, 2012) or ghost fishing of fragile species (Anderson et al., 2009; Filmalter et al., 2013). Assessing the magnitude of some of these impacts, such as levels of bycatch, does not necessarily rely on an improved knowledge on the modalities of FOB use. This is not the case of other impacts, such as the contribution of FOBs to overfishing of yellowfin and bigeye tuna stocks. Mitigating these impacts by appropriate management decisions therefore requires more information on FOB use (Davies et al., 2014). The present thesis contributes to a better understanding of strategies with FOBs from their deployment to the end of their time at sea.

Since the development of FOB fisheries during the 1990s, modalities in the use of FOBs had mainly been examined through the seasonal distribution of fishing sets. For the first time, French GPS buoy tracks were available opening the possibility to examine the modalities in GPS buoy deployment. Interviews with skippers suggested that these data could be used to investigate the zones, the seasons and the currents used for the deployment of new dFADs and new GPS buoys. In chapter 2, a clustering method was used to identify zones and seasons of deployment of GPS buoys from 2007 to 2013 in the Atlantic and Indian Oceans. Four seasons of GPS buoy deployment were identified in each ocean, with a stronger seasonality in the Indian Ocean. GPS buoy deployments were also found to be strongly related to seasonal currents and seasonal patterns of FOB fishing. Such results were expected and remained relatively close to the first descriptions of the fishery (Ariz et al., 1999; Hallier and Parajua, 1992). However, they provide insights into different aspects of the behaviour of fishers, which is generally key to a better management of fisheries (Fulton et al., 2011). In particular, as FOB deployment and fishing activities are strongly correlated in time and space, this indicates a high turnover of GPS buoys on FOBs, through frequent GPS buoy transfers (i.e. appropriation of foreign FOBs). As a consequence, the sole examination of a number of active GPS buoys may not be representative of the total fishing effort deployed on FOBs, as purse seiners may also use the objects owned by other vessels.

Nevertheless, our results should only be seen as first step and additional analyses and complementary information are still required. One of the major limitations of the present results is the absence of GPS buoy data for the Spanish fleet in the Atlantic and Indian Oceans and for other fleets (e.g. Ghana) in the Atlantic Ocean, as well as the lack of information on support vessels in the Atlantic Ocean. In chapter 2, this prevented the comparison of seasons of GPS buoy deployment among fleets. This is far from being a minor limitation, especially as Spanish and Other fishing fleets use more FOBs and support vessels than the French fleet (Ramos et al., 2010). In chapter 3, we demonstrated that this significantly increased their fishing efficiency. Support vessels may be used to anticipate GPS buoy deployment seasons by a few weeks or a few months. This could strongly modify fishing strategies of associated purse seiners and their chances to catch fish, particularly during periods of transition from one fishing ground to another. This assumption could easily be verified, even in the absence of detailed GPS buoy data for the Spanish and Other fleets. Information collected through FAD logbooks of purse seiners and support vessel logbooks could provide the positions of GPS buoy deployment for such verification (e.g. Assan et al. 2015).

In addition, interviews with purse seine skippers have further underlined the dynamic nature of the fishery. In just two years, due to increasing numbers of GPS and echosounder buoys, French skippers had started to change their FOB deployment strategies (chapter 4). In 2013, they indicated that their limited amount of GPS buoys obliged them to be relatively selective in their deployments (for example based on expected drift or potential losses). In 2015, fishers had become slightly less selective, regardless of the potential negative impacts of these changes. This simple observation demonstrates the need for a constant monitoring of the fast changes occurring in the fishery. In chapters 2 and 3, such changes were documented over 2007-2013 and 2003-2014, respectively. We provide alternatives to previous use of available data, that often placed more emphasis on providing indices of CPUE, than on monitoring strategic and technological changes (with some important exceptions, e.g. Gaertner and Pallarés, 2002; Davies et al., 2014; Lopez et al., 2014; Torres-Irineo et al., 2014). However, as our results extend no further than 2014, they may be partially outdated already. This is particularly true when it comes to the numbers of dFADs and GPS buoy-equipped FOBs estimated in chapter 2.

Yet, providing such estimates is a considerable step already. In recent years, the increasing use of dFADs and GPS buoys had been hypothesized (Davies et al., 2014; Fonteneau and Chassot, 2014) but could not be verified. Several authors had made attempts to provide an estimate of FOB use but these estimates suffered from lack of data and approximate definitions (Baske et al., 2012; Ménard et al., 2000; Moreno et al., 2007). In chapter 2, these two issues were addressed with a transparent and objective methodology. For the first time, French GPS buoy tracks were combined with data collected by onboard observers to obtain an estimate of the total number of FOBs used by all fleets, as well as the uncertainty in this estimate. This methodology could easily be applied in the future if detailed information on dFAD and GPS buoy use is not available to tuna RFMOs. In this methodology, clear and simple definitions, explicitly separating FOBs deployed by purse seiners (dFADs) from those naturally drifting at sea (logs) were adopted. We assumed that purse seiners may impact tropical ecosystems by two means: (i) directly, through the deployment of dFADs that modify the environment of tuna (Dagorn et al., 2013a) and (ii) indirectly by increasing fishing efficiency (Fonteneau et al., 2000; Le Gall, 2000) through the monitoring of dFADs and logs with GPS and echo-sounder buoys while they drift. Similarly, we considered that there was a difference between a number of GPS buoy deployments (providing information on strategies with FOBs) and a number of GPS buoy equipped FOBs drifting at sea (providing information on FOB fishing effort).

These definitions were used to improve the quality of observer data used in chapter 2. Onboard observers are generally neither professionals nor experts of the fishery but they have to report various information: bycatch levels and composition, general activities of purse seiners (e.g. searching or fishing activities) as well as detailed information on FOB use. Over 2007-2013, the information they had to collect on FOB activities was sometimes too precise to be correctly reported. For example, when observers reported the type of FOBs, they had the choice between almost 20 categories of FOBs, which added confusion. At the same time, the collection of such data lacked clear objectives. This is not surprising, as observer data are primarily collected to survey bycatch and FOB activities of purse seiners are only a "by-product" of observers programs. However, this introduced a number of incorrect information in the data. For example, as it was not clear that the data could be used to monitor modifications of the natural habitat as well as changes in fishing effort, some observers considered that deploying a dFAD or a GPS buoy were equivalent activities. The varying quality of the data implied a long correction process (more than one month in total to correct about 15,000 observations), possibly introducing mistakes in the corrected data, due to our own understanding of the data collected by each observer. This illustrates the need to continuously adapt sampling and observation protocols so as to monitor the evolution of fisheries and address new scientific questions or management issues. In some cases, the information available from historical observer reports should be recovered and updated with current data formats to permit long-term assessments of the fisheries and ecosystem changes.

6.2.3 Improved understanding of the consequences of FOB use

Results obtained in chapter 2 showed that the use of dFADs had been multiplied by 7.0 in the Atlantic Ocean and 4.2 in the Indian Ocean between 2007 and 2013. Part of this increasing use of dFADs and GPS buoys certainly contributed to the increasing proportion of fishing sets on FOBs identified in chapter 3. Over time, purse seiners increased their use of FOBs to improve their catches (chapter 3) or to reduce the competition with other purse seiners (chapter 4). Our results demonstrate that dFADs are now the dominant form of FOBs in the Atlantic and Indian Oceans (> 90%) and that their density has dramatically increased in recent years. However, a significant proportion of GPS buoy tracked FOBs may not contribute to fishing effort. The increasing use of FOBs could lead to increased ghost fishing effort (with dFADs drifting outside fishing grounds, chapter 1), destruction of fragile habitats and pollution (when dFADs beach on the coasts, chapter 1) or disturbance to tuna behaviour (due to habitat modification, chapters 2 and 4). In the case of ghost fishing effort and FOB beaching, the impacts of the fishery are likely to be proportional to the increase in the use of FOBs and may therefore have been multiplied by 7.0 in the Atlantic Ocean and 4.2 in the Indian Ocean. The implementation of non-entangling dFADs in recent years has likely reduced the magnitude of ghost fishing although the evolution of "sausage-nets" after several months at sea remains poorly quantified and difficult to evaluate. In addition, an increasing density of FOBs or an increasing proportion of dFADs in the population of FOBs (described in chapter 2) may imply a modification of tuna migrations, body condition or aggregative behaviour (Hallier and Gaertner 2008, Wang et al. 2012, Robert et al. 2014, Sempo et al. 2013). Estimated densities of FOBs could be combined with catch, bycatch, ghost-fishing and echo-sounder buoy data for instance to test for the effects of school fragmentation. Besides, biological data could be collected to understand the effect of FOBs on the biology of tropical tunas, such as information on fatty acids to investigate some effects of tuna aggregative behaviour on their trophic ecology (Sardenne et al., 2015). This would require a well balanced sampling design to disentangle the expected effects of dFADs on tuna biology from their effects on tuna ecology. This would turn our estimates of FOBs into improved measures of the impacts of the fishery.

This is necessary, as there is still little concrete scientific evaluation surrounding a number of these impacts, though they have received much attention (e.g. regarding the potential for an ecological trap, ISSF 2014).

During our research, we unsuccessfully tried to provide such measures. For example, we explored the relationship between estimated densities of GPS buoy equipped FOBs and catches. Our objective was to verify the possibility of a fragmentation of tuna schools due to increasing densities of FOBs (Sempo et al., 2013). The high level of uncertainty in our estimates (due to the absence of Spanish and other fleet GPS buoy data) and the absence of spatial structure in PS catches (Saulnier, 2014) prevented further analyses. In chapter 4, interviews with skippers were proposed as a solution to compensate for this absence of results. Yet, purse seine skippers had different points of view (chapter 4) on the magnitude of the changes induced by FOBs, preventing the formulation of clear assumptions regarding the modification of tuna schooling behaviour. We also unsuccessfully tried to provide a measure of nominal fishing effort, and thus failed at defining a measure of effective fishing effort, based on the estimated densities of FOBs and a separation of the time purse seiners dedicate to FOBs and FSC activities (discussed in chapter 3). However, it was still possible to provide useful information for the management of PS fleets in the Atlantic and Indian Oceans, by measuring the contribution of FOBs to the fishing efficiency of purse seiners.

The massive use of FOBs by tropical tuna purse seiners was known to have a particularly important impact on their fishing efficiency (Ariz Telleria et al., 1999; Fonteneau et al., 2000; Hallier et al., 1992). However, apart from theoretical approaches, previous analyses had not considered the effect of strategies with FOBs (Le Gall, 2000) nor the contribution of support vessels to the efficiency of tropical tuna purse seiners (except in Pallarés et al., 2002). In addition, updated indices of fishing efficiency were necessary, as an unlikely constant increase in effective fishing effort is generally assumed within ICCAT and IOTC working groups involved in stock assessments, i.e. 3% per year derived from Gascuel et al., (1993) and Fonteneau et al., (1999). In chapter 3, logbook data from the French and the Spanish fleets were used to examine changes in five dimensions of the efficiency of tropical tuna purse seiners: their catch per day, catch per fishing set, catch per distance, number of fishing sets per day and travelled distance per day. Results indicated a progression of the fishing efficiency of purse seine fleets over 2003-2014, ranging from 0.3% to 1.5% per year in the Atlantic Ocean and from 0.9% to 2.2% in the Indian Ocean. There are a number of potential limitations to these results. For example, we did not consider the effects of technological changes identified by previous studies (Gaertner and Pallarés, 2002; Torres-Irineo et al., 2014) or the recent introduction of echosounder buoys (Lopez et al., 2014) in our analyses. Also, we could not directly include the number of active GPS buoys of each purse seiner in the models. However, we measured the consequences of increasing numbers of FOBs on the fishing strategy of purse seiners and their fishing efficiency. We also provided crucial information regarding the effect of support vessels to the efficiency of purse seiners, yet only in the Indian Ocean.

6.3 Recommendations and perspectives

6.3.1 Data provided to tuna RFMOs

Our research as well as the work of other participants of the EU project CECOFAD highlighted important issues of data collection and definitions (Gaertner et al., 2016). In particular, we identified that the term “FAD” was either used to describe any type of object floating at the surface of the ocean or to describe objects that had specifically been designed to aggregate tropical tunas. Inconsistent use of the same term for different categories of objects prevents the comparison of sources of information on FOB use. This could even lead to a misinterpretation of such information or to inappropriate management decisions. To overcome these issues, common definitions were adopted through a collaborative work between EU fisheries scientists and representatives of EU fishing companies. Three objectives were identified: (i) measuring the level of habitat modification due to the introduction of a large number of artificial objects (dFADs) at sea, (ii) measuring changes in fishing effort and fishing efficiency due to tracking devices such as GPS or echosounder buoys and finally (iii) measuring potential pollution due to losses of dFADs and their tracking devices. Adopted definitions are summarised in figure 6.1, along with other propositions of definitions to estimate the use of FOBs and their consequences. Among others, it is important to note that reporting a number of GPS buoy/ dFAD deployment is different from reporting a number of active GPS buoys / GPS buoy-equipped dFADs. This is for instance related to the high rate of GPS buoy transfers (when purse seiners or support vessels replace GPS buoy of foreign FOBs) or to the deactivation of GPS buoys of lost FOBs. A recommendation of the present thesis would be to use such unified definitions for research purposes as well as in the data reported to tuna RFMOs in FAD management plans.

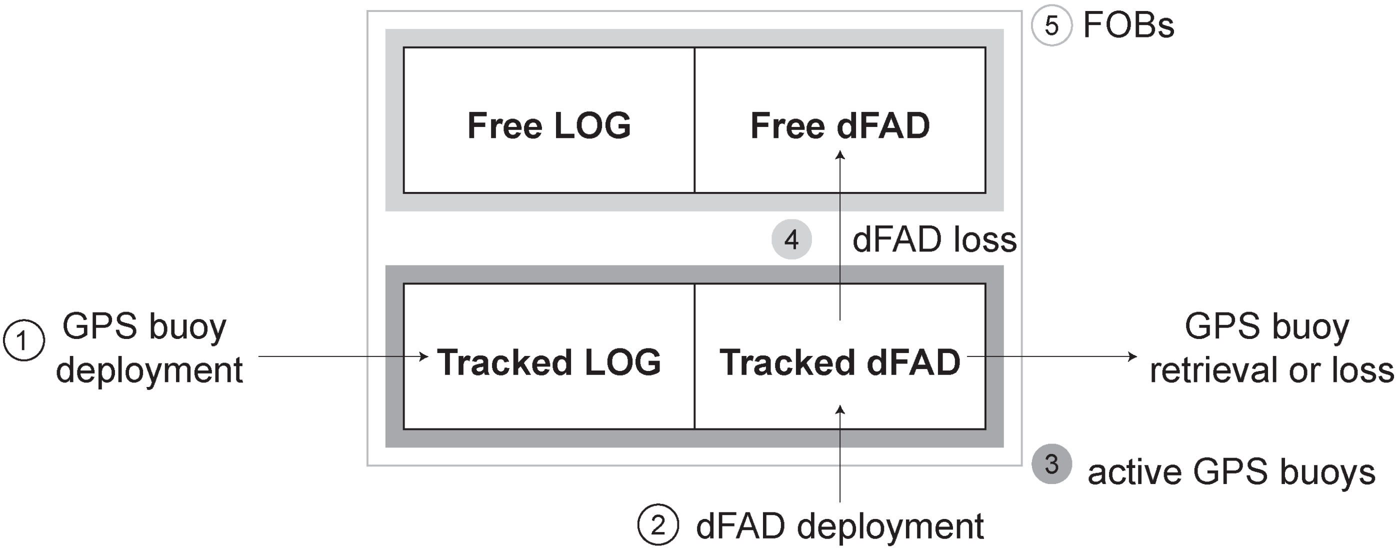


Figure 6.1: proposed typology of FOBs and activities with FOBs. In particular, we propose to separate FOBs into two simple categories: dFADs (specifically designed to aggregate tunas) and logs (FOBs that are not dFADs). We also propose to clearly separate estimates of GPS buoy deployment, dFAD deployment and active GPS buoys to avoid confusion in FAD management plans.

One of the main contributions of our research is the evaluation of the effect of FOBs and support vessels to the efficiency of tropical tuna purse seiners. Detailed information on the use of FOBs by all purse seine fleets is not required by tuna RFMOs. This information was only available for the French fleet, through an agreement between IRD and ORTHONGEL. This provided the basis for an extrapolation of the number of French GPS buoys to a total number of dFADs and GPS buoy-equipped FOBs. Nevertheless, such extrapolation would not be necessary if each purse seine fleet provided fine scale estimates of their use of GPS buoys. Obviously, confidentiality of such data is important for fishing companies. A solution would be to provide anonymised data, aggregated at sufficiently fine spatio-temporal scales (1° and 1 month for example) to be used for scientific purposes. Another solution would be to provide detailed data of each fleet to corresponding scientific institutes with a few months of delay (for example 6 months that exceeds the average 1-2 month lifespan of GPS buoys, chapter 1). This last solution has been adopted by the French purse seine fleet and the IRD since 2007.

Similarly, data on the collaboration between purse seiners and their support vessels is rarely available, even to tuna RFMOs in stock assessment working groups. For the present thesis, we only had access to this information for the Indian Ocean, through collaboration with the Seychelles Fishing Authority. Therefore, we could not compare the results we obtained for the Indian Ocean to the situation of the Atlantic Ocean. Getting information on support vessels may be slightly more difficult than collecting information GPS buoy use, as support vessels often operate under convenience flags. However, providing information on the number of support vessels and their activities is mandatory in tuna RFMOs. Our results demonstrate that corresponding ICCAT (14-01) and IOTC resolutions (15/04) should not only be correctly implemented but that they should also be complemented by information on the purse seiners that support vessels are assisting. A recommendation of the present thesis is that this information should be routinely provided on logbooks of support vessels and/or on logbooks of purse seiners, either at the scale of the month or at the scale of the fishing trip.

For a better evaluation and management of the tropical tuna PS fisheries, the collection of information on dFADs, tracking devices (GPS and echosounder buoys), and support vessels should be reinforced. In theory, FOB management plans should meet these objectives of data collection and fishing fleets should be accountable to tuna RFMOs regarding their fishing vessels as well as their fishing gears (including their dFADs and tracking devices) and their fishing capacity (including their support vessels). In a context of growing pressure for the management of the purse seine fishery, having access to detailed information on support vessel and FOB use becomes increasingly important. Such information would provide the basis for an objective assessment of the impacts of the fishery, appropriate decisions to mitigate the impacts of FOB use.

6.3.2 Fishing effort and fishing efficiency of tropical tuna purse seiners

Measuring and controlling fishing effort is central to fisheries assessment and management. In particular, in the absence of fishery-independent data, commercial catch and effort data are traditionally used to derive CPUE indices that are used as abundance indices in stock assessment models and form the basis for scientific diagnosis. During the last decades, global fishing effort has dramatically increased (Pauly et al., 2002; Watson et al., 2013; Worm et al., 2009), leading to issues of excess capacity and excess fishing effort (Greboval and Munro, 1999). Over time, all tuna RFMOs have experienced growing concerns regarding the impacts of the activities of purse seiners. Therefore, estimating the fishing effort exerted by purse seine fleets on tropical tuna stocks seems more required than ever. Though necessary for a proper evaluation and management of the impacts of purse seine fishing in all oceans, this has always been a challenge (Bez et al., 2011b; Fonteneau et al., 1999; Gascuel et al., 1993). The massive and increasing use of FOBs still prevents the definition of an appropriate measure of fishing effort for tropical tuna fisheries. Separating the effort between FSC and FOB activities to provide a measure of effective FOB fishing effort was one of the objectives of the present thesis. Due to data availability, this objective could not be met. The availability of operational fisheries data (i.e. GPS and echosounder buoy, VMS, observer data, information on support vessels) from all fishing fleets could provide a mean to distinguish between FSC and FOB effort. Nevertheless and despite new management measures as well as increased pressure from NGOs and consumers, this seems highly unlikely in a near future.

As stated previously, providing an appropriate measure of fishing effort can be necessary to improve CPUE standardisation and provide reliable abundance indices. So far, this has hindered the use of purse-seine catch rates for the estimation of tuna abundances needed for stock assessment (Fonteneau et al., 2013; ISSF, 2012). As a result, tuna RFMOs rely on longline CPUEs for stock assessment, though standardised longline CPUEs only provide information for the adult fraction of tuna populations and rarely incorporate information on technological changes (Gaertner et al., 2016). In the absence of an appropriate measure of fishing effort for tropical tuna purse seiners, alternative methods have been proposed to produce fishery-independent indices of abundance for tropical tunas and other species associated with FOBs. First, VMS data have been shown to be promising to derive CPUEs for purse seine tuna fisheries (Bez et al. 2011, Walker et al. 2015). Second, acoustic data derived from FOB echosounder buoys could be combined with behavioural models (Capello et al., 2015; Santiago et al., 2015) and estimates of species composition obtained from multispecies samples at port. This could provide information on the aggregated skipjack biomass and information on seasonal or annual recruitment for yellowfin and bigeye (see below). Such approaches require fine scale data from echosounder buoys through the collaboration between fisheries scientists and representatives of fishing companies. Tuna RFMOs and governments should be involved in their collection to ensure the confidentiality of the data (Gaertner et al., 2016). Third, time series of YFT and BET recruitment estimated from complex age-structure models could be combined with estimates of species composition to provide information on SKJ abundance for which assessments remain the most uncertain.

Nevertheless, although providing reliable indices of abundance is essential for stock assessment, this should not be our sole objective. Standardising CPUEs to provide indices of abundance or indices of fishing power require similar data (logbooks, vessel characteristics, etc) and statistical approaches (GLMs, GLMMs, etc). CPUE standardisation procedures could therefore also be used to monitor changes in the efficiency of purse seiners, even in the absence of an appropriate measure of fishing effort. Surprisingly, this is not done in stock assessment Working Groups of tuna RFMOs. A proposition of the present thesis would be to conduct two types of CPUE standardisation each year: (i) a standardisation at the scale of the fishing set to provide information on the abundance of skipjack, yellowfin and bigeye tuna (ii) a standardisation at the scale of the fishing trip or at the scale of the month to monitor the effect of technical and strategic changes on the efficiency of tropical tuna purse seine fleets. For the second objective, multiple indices of fishing efficiency may be considered as in chapter 3, so as to depict the different dimensions of the efficiency of purse seine fleets. Once again, it should be stressed that detailed data on the use of tracking devices (GPS buoys and echosounder buoys) and support vessels would be much needed to meet this objective. We acknowledge that such data are sensitive for fishing companies and such approaches are time consuming for researchers. However, they would enhance the monitoring of the fishery and inform the necessary management decisions.

6.3.3 Management of FOB fisheries

In recent years, tropical tuna fisheries have been increasingly criticised about their numerous FOBs. In particular, their impacts on bycatch species, the increased fishing pressure as well as the apparent lack of management have become communication tools for some environmental NGOs in their anti-FAD campaigns (e.g. http://www.greenpeace.org/france/fr/campagnes/oceans/arrethon/). Since the beginning of the 2010s, there are growing pressures on tuna consumers and seafood brands to avoid tuna caught on FOBs (Davies et al., 2015). However, prohibiting dFAD deployment and FOB fishing would be a rather radical solution that is unlikely to be adopted by tuna RFMOs. Such a decision may not be suitable as fishing on FOBs has become vital to tropical tuna purse seine fisheries, and in particular to the Spanish purse seine fleet (Davies et al., 2014 and chapter 3). In addition, choosing between FSC and FOB fishing implies a choice between two very different economic models (Guillotreau et al., 2011), as FSC catches are mainly dominated by large yellowfin tuna that can be sold as high quality fish whilst FOB catches are mainly dominated by skipjack tuna destined for canning. Banning FOB fishing could have a significant effect on the profitability on fishing companies that have adopted a dominant FOB strategy but also on tuna markets and supplies. Among others, banning the use of dFADs would significantly reduce skipjack catch (Guillotreau et al., 2011), which in turn would affect the canning industry and tuna consumers, as canned tuna is a major source of affordable proteins worldwide (Dagorn et al., 2013; Miyake et al., 2010). This would also redirect fishing effort on yellowfin tuna stocks that are already considered as overfished in the Indian Ocean (IOTC, 2015) and were overfished in the past in the Atlantic Ocean (ICCAT, 2015) which is obviously not be suitable.

Nevertheless, the increasing criticism of FOB fishing may indicate that tuna RFMOs have failed in making the appropriate management decisions when they were necessary. Concerns regarding the consequences of FOB use have been discussed at least since the 1990s (e.g. Hallier et al., 1992; Stretta et al., 1998) and the lack of data to measure their magnitude has been pointed out at least since the 2000s (Bromhead et al., 2003; Fonteneau et al., 2000). But increasing deployments of dFADs have long had little obvious effects on the state of tropical tuna stocks, and therefore specific FOB management decisions have not been made, except for the implementation of spatial closures. These seasonal FOB moratoria or seasonal fishing closures have had a limited effect on catches of yellowfin and bigeye tuna juveniles (Davies et al., 2014; Fonteneau and Chassot, 2014; Fonteneau et al., 2015). Besides, they were unlikely to have an impact on the use of FOBs and their number has continuously increased over time, even leading to a race-to-fish in recent years (chapters 2 and 4). Encouraging progress have been made with the implementation of FAD management plans (ICCAT Res 15-01, IOTC Res 15-09), the design of non-entangling dFADs (Franco et al., 2012) or the recent limitation of the number of GPS buoys in the Atlantic and the Indian Oceans (ICCAT Res 15-01, IOTC Res 15-08). Yet, problems of overcapacity and overfishing are still insufficiently addressed by these recent decisions. In particular, interviews with French skippers have revealed in chapter 4 the potential counterproductive effect of setting a too high limitation on the number of active GPS buoys. If 550 active GPS buoys is not enough restrictive, some fishing companies will not be affected, while others may be tempted to increase their use of FOBs. Applying a Precautionary Approach to tropical tuna purse seine fisheries, and more generally to all tropical tuna fisheries, may require going a step further, for example within Management Strategy Evaluations (MSE) that would allow to test for potential management scenarios, even in the absence of detailed information on FOB use and fishers behaviour.

Throughout this thesis, we have highlighted the importance of improving the monitoring of the fishery through a better data collection, including information on GPS buoys of all fleets, detailed echosounder buoy data and collaboration between purse seiners and their support vessels. Such data would be necessary to measure the impacts of FOB fishing on pelagic ecosystems as well as to investigate changes in fishing effort and fishing efficiency. We have also emphasised the need for a better management of the fishery that should preferably combine multiple management tools: a limitation of the use of dFADs and FOB tracking devices, an improved control of support vessels, a regulation on fleet capacity accounting for FOB use and other tropical tuna fishing fleets and/or a catch quotas (chapter 4). Some of these regulations already exist, as the ICCAT and the IOTC have for example adopted capacity limitation resolutions (ICCAT Res 15-01, IOTC Res 15-01). They are however not specific to FOBs and have not had the expected outcomes (Aranda et al., 2012) and tropical tuna purse seine fleets may consider a voluntary reduction of their fishing capacity. Improving the management of the fishery is not an easy task, especially as this management should not only focus on tropical tuna purse seiners, but address other issues such as the lack of knowledge on artisanal fisheries, the problems induced by reflagging or the question of IUU fishing. To be effective, management decisions should ideally be made at a global scale with the cooperation of all tuna RFMOs so as to avoid transfers of vessels between oceans in response to management decisions. Tuna RFMOs have started recently experimenting "FAD working groups", joint sessions of these meetings could be used to synchronize management decisions among oceans. Finally, all stakeholders should be involved in a process of co-management of the fishery. Their knowledge, their perceptions and their point of view should be treated as carefully as quantitative sources of information to anticipate the consequences of management decisions and improve governance.

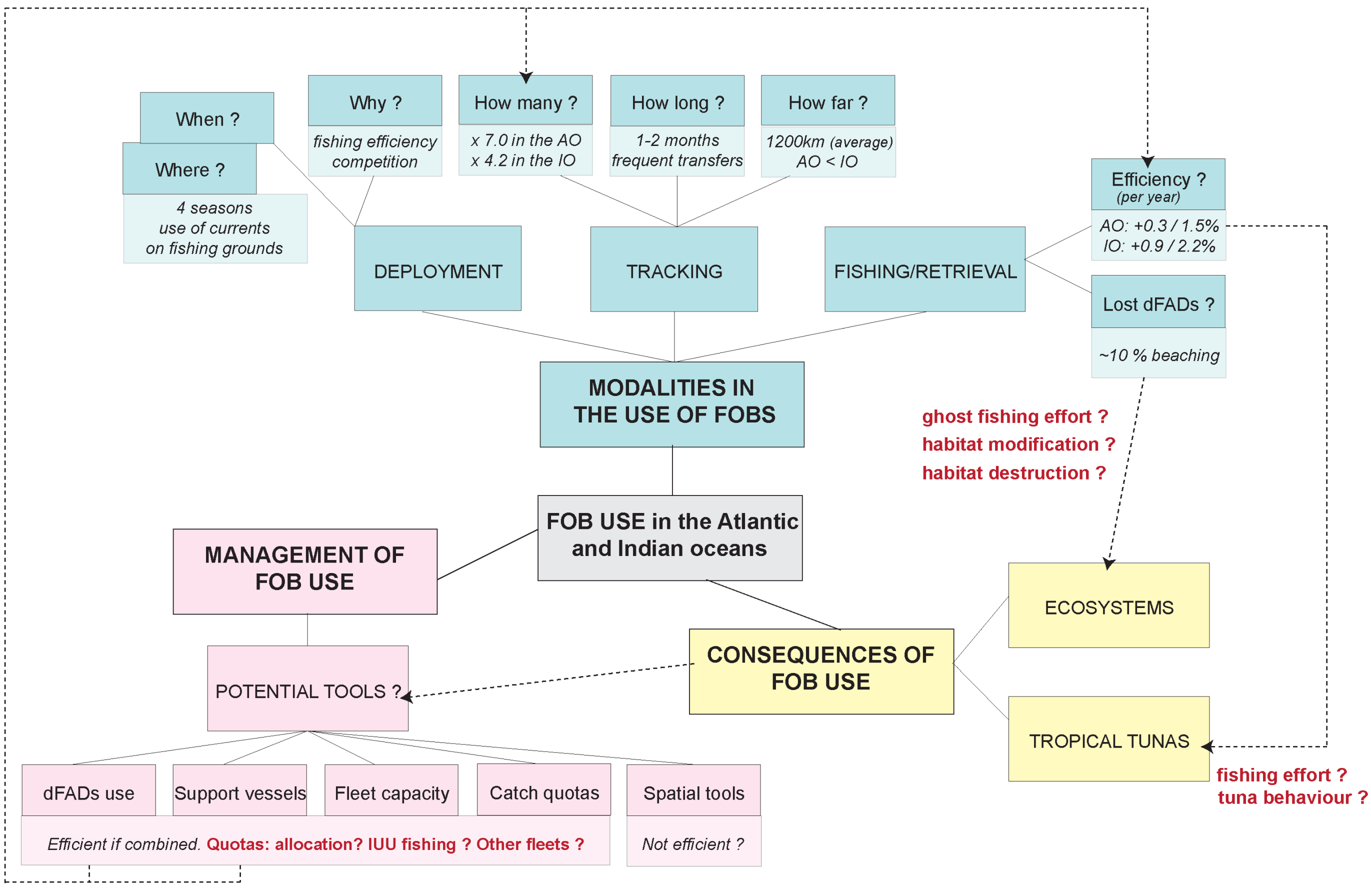


Figure 6.2: summary of the questions addressed by our research and main findings. Three main topics were addressed: the modalities in the use of FOBs, their consequences and the potential management of the fishery. There are still important questions to address regarding the impacts of FOB use on pelagic ecosystems.

To conclude, the present thesis offered insights into FOB fisheries and provided answers regarding when, where and how tropical tuna purse seiners have used dFADs and GPS buoys in the Atlantic and Indian Oceans. Our research demonstrated the massive and increasing use of FOBs in recent years and its contribution to a significant improvement of the fishing efficiency of tropical tuna purse seiners. Important management decisions have now to be made to improve the sustainability of the fishery in the future, potentially through a reduction of fishing capacity, catch quotas or a better monitoring of support vessels. Though dFADs, and more generally FOBs, have negative impacts on tropical tunas (bycatch of juveniles, increased fishing effort) or on marine ecosystems (bycatch, ghost fishing, beaching or pollution), they are not necessarily destructive fishing gears. However, an inappropriate monitoring and management of their use could have disastrous consequences.

References

Agnew, D. J., Pearce, J., Pramod, G., Peatman, T., Watson, R., Beddington, J. R., and Pitcher, T. J. 2009. Estimating the worldwide extent of illegal fishing. PloS one, 4: e4570.

Airaud, M., and Tézenas du Montcel, L. 2015. Une « recherche-action » auprès d'acteurs de la pêcherie thonière tropicale à la senne : réflexions et perspectives. GAP 2 Project ' Tuna FAD Fisheries. Sustainably managing tuna fisheries using fish aggregating devices '.

Amandè, M. J., Ariz, J., Chassot, E., de Molina, A. D., Gaertner, D., Murua, H., Pianet, R., et al. 2010. Bycatch of the European purse seine tuna fishery in the Atlantic Ocean for the 2003–2007 period. Aquatic Living Resources, 23: 353–362.

Amandè, M. J., Ariz, J., Chassot, E., de Molina, A. D., Gaertner, D., Murua, H., Pianet, R., et al. 2011. Bycatch of the European purse seine tuna fishery in the Atlantic Ocean for the 2003–2007 period. Aquatic Living Resources, 23: 353–362.

Amandè, M. J., Chassot, E., Chavance, P., Murua, H., Molina, A. D. de, and Bez, N. 2012. Precision in bycatch estimates: the case of tuna purse-seine fisheries in the Indian Ocean. ICES Journal of Marine Science: Journal du Conseil. http://icesjms.oxfordjournals.org/content/early/2012/06/15/icesjms.fss106 (Accessed 9 July 2012).

Anderson, R. C., Zahir, H., Jauharee, R., Sakamoto, T., Sakamoto, I., and Johnson, G. 2009. Entanglement of Olive Ridley Turtles Lepidochelys olivacea in ghost nets in the equatorial Indian Ocean. IOTC-2009-WPEB-07.

Aranda, M., Murua, H., and de Bruyn, P. 2012. Managing fishing capacity in tuna regional fisheries management organisations (RFMOs): Development and state of the art. Marine Policy, 36: 985–992.

Ariz, J., Delgado de Molina, A., Fonteneau, A., Gonzales Costas, F., and Pallarés, P. 1999. Logs and tunas in the eastern tropical Atlantic: a review of present knowledge and uncertainties. In Proceedings of the International Workshop on the Ecology and Fisheries for Tunas Associated with Floating Objects February 11-13, pp. 21–65. Scott, M.D. et al., La Jolla, California.

Arrizabalaga, H., Ariz, J., Mina, X., de Molina, A. D., Artetxe, I., Pallares, P., and Iriondo, A. 2001. Analysis of the activities of supply vessels in the Indian Ocean from observers data. Doc. IOTC.

Assan, C., Lucas, J., Maufroy, A., Chassot, E., and Delgado de Molina, A. 2015. Seychelles auxiliary vessels in support of purse seine fishing in the Indian Ocean during 2005-2014. 17ème groupe de travail sur les thons tropicaux. CTOI, Victoria, IOTC-WPTT17-41.

Balderson, S., and Martin, L. E. C. 2015. Environmental impacts and causation of 'beached' Drifting Fish Aggregating Devices around Seychelles Islands: a preliminary report on data collected by Island Conservation Society. IOTC WPEB.

Balton, D. A. 1996. Strengthening the law of the sea: The new agreement on straddling fish stocks and highly migratory fish stocks. Ocean Development & International Law, 27: 125–151.

Bard, F.-X., Stretta, J.-M., and Slepoukha, M. 1985. Les épaves artificielles comme auxiliaires de la pêche thonière en océan Atlantique : quel avenir ? Pêche Maritime: 655–659.

Baske, A., Gibbon, J., Benn, J., and Nickson, A. 2012. Estimating the Use of of Drifting Fish Aggregation Devices Around the Globe - Pew Environment Group.

Beddington, J. R., Agnew, D. J., and Clark, C. W. 2007. Current problems in the management of marine fisheries. science, 316: 1713–1716.

Bertrand, S., Diaz, E., and Lengaigne, M. 2008. Patterns in the spatial distribution of Peruvian anchovy (Engraulis ringens) revealed by spatially explicit fishing data. Progress in Oceanography, 79: 379–389.

Beverton, R. J. H., and Holt, S. J. 1957. On the Dynamics of Exploited Fish Populations. Fisheries investigations series 2. Ministry of Agriculture, Fisheries and Food.London, UK. 541 pp.

Bez, N., Walker, E., Gaertner, D., Rivoirard, J., and Gaspar, P. 2011a. Fishing activity of tuna purse seiners estimated from vessels monitoring system (VMS) data. Canadian Journal of Fisheries and Aquatic Sciences, 68: 1998–2010.

Bez, N., Walker, E., Gaertner, D., Rivoirard, J., and Gaspar, P. 2011b. Fishing activity of tuna purse seiners estimated from vessels monitoring system (VMS) data. Canadian Journal of Fisheries and Aquatic Sciences, 68: 1998–2010.

Birnie, P. 1993. Reflagging of fishing vessels on the high seas. Review of European Community & International Environmental Law, 2: 270–276.

Bjørndal, T., Kaitala, V., Lindroos, M., and Munro, G. R. 2000. The management of high seas fisheries. Annals of Operations Research, 94: 183–196.

Botsford, L. W., Castilla, J. C., and Peterson, C. H. 1997. The Management of Fisheries and Marine Ecosystems. Science, 277: 509–515.

Braccini, J. M., O'Neill, M. F., Campbell, A. B., Leigh, G. M., and Courtney, A. J. 2012. Fishing power and standardized catch rates: implications of missing vessel-characteristic data from the Australian eastern king prawn (Melicertus plebejus) fishery. Canadian Journal of Fisheries and Aquatic Sciences, 69: 797–809.

Branch, T. A. 2008. Not all fisheries will be collapsed in 2048. Marine Policy, 32: 38–39.

Bratten, D., and Hall, M. 1996. Working with fishers to reduce bycatch: The tunadolphin problem in the eastern Pacific Ocean. Fisheries Bycatch: Consequences and Management.

Breiman, L. 2001. Random Forests. Machine Learning, 45: 5–32.

Bromhead, D., Foster, J., Attard, R., Findlay, J., and Kalish, J. 2000. A Review of the impact of fish aggregating devices (FADs) on tuna fisheries. Final report to Fisheries Resources Research Fund. Australian Bureau of Rural Science, Canberra. http://adl.brs.gov.au/brsShop/data/PC12777.pdf.

Bromhead, D., Foster, J., Attard, R., Findlay, J., and Kalish, J. 2003. A Review of the impact of fish aggregating devices (FADs) on tuna fisheries. Final report to Fisheries Resources Research Fund. Australian Bureau of Rural Science, Canberra.

Caddy, J. F. 1999. Fisheries management in the twenty-first century: will new paradigms apply? Reviews in Fish Biology and Fisheries, 9: 1–43.

Caddy, J. F., and Cochrane, K. L. 2001. A review of fisheries management past and present and some future perspectives for the third millennium. Ocean & Coastal Management, 44: 653–682.

Caddy, J. F., and Majkowski, J. 1996. Tuna and trees: a reflection on a long-term perspective for tuna fishing around floating logs. Fisheries research, 25: 369–376.

Caddy, J. F., and Seijo, J. C. 2005. This is more difficult than we thought! The responsibility of scientists, managers and stakeholders to mitigate the unsustainability of marine fisheries. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 360: 59–75.

Capello, M., Soria, M., Cotel, P., Potin, G., Dagorn, L., and Fréon, P. 2012. The heterogeneous spatial and temporal patterns of behavior of small pelagic fish in an array of Fish Aggregating Devices (FADs). Journal of Experimental Marine Biology and Ecology, 430: 56–62.

Castro, J., Santiago, J., and Santana-Ortega, A. 2002. A general theory on fish aggregation to floating objects: An alternative to the meeting point hypothesis. Reviews in Fish Biology and Fisheries, 11: 255–277.

Champagnat, C., and Le Marrec, R. 1972. La pêche thonière à Dakar en 1970 et 1971.

Chalmers, N., and Fabricius, C. 2007. Expert and Generalist Local Knowledge about Land-cover Change on South Africa's Wild Coast: Can Local Ecological Knowledge Add Value to Science? Ecology and Society, 12: 10.

Chassot, E., Dewals, P., Floch, L., Lucas, V., Morales-Vargas, M., and Kaplan, D. M. 2010. Analysis of the effects of Somali piracy on the European tuna purse seine fisheries of the Indian Ocean. In IOTC Scientific Committee Proceedings, pp. 1–26. Indian Ocean Tuna Commission, Seychelles. http://www.iotc.org/files/proceedings/2010/sc/IOTC-2010-SC-09.pdf.

Chassot, E., Assan, C., Damiano, A., Delgado de Molina, A., Joachim, L., Cauquil, P., Lesperance, F., et al. 2015a. Statistics of the European Union and associated flags purse seine fishing fleets targeting tropical tunas in the Indian Ocean during 1984-2014. IOTC-2015-WPTT17-12.

Chassot, E., Floch, L., Dewals, P., Irié, D., Tamegnon, A., Cauquil, P., Amandè, M. J., et al. 2015b. Statistics of the French purse seine fishing fleet targeting tropical tunas in the Atlantic Ocean (1991-2013). Collect . Vol. Sci. Pap., 71 (1). ICCAT.

Chassot, E., Goujon, M., Maufroy, A., Cauquil, P., Fonteneau, A., and Gaertner, D. (2014). The use of artificial fish aggregating devices by the French tropical tuna purse seine fleet: Historical perspective and current practice in the Indian Ocean.

Christy, F. T., and Scott, A. 2013. The Common Wealth in Ocean Fisheries: Some Problems of Growth and Economic Allocation. Routledge. 320 pp.

Clark, N. A., Ardron, J. A., and Pendleton, L. H. 2015. Evaluating the basic elements of transparency of regional fisheries management organizations. Marine Policy, 57: 158–166.

Clifford, P., and Richardson, S. 1985. Testing the association between two spatial processes. Statistics and Decisions, 2: 155–160.

Cullis-Suzuki, S., and Pauly, D. 2010. Failing the high seas: A global evaluation of regional fisheries management organizations. Marine Policy, 34: 1036–1042.

Cushing, D. H. 1988. The Provident Sea. Cambridge University Press. http://www.cambridge.org/us/academic/subjects/life-sciences/natural-resource-management-agriculture-horticulture-and/provident-sea (Accessed 12 February 2016).

Cutler, D. R., Edwards, T. C., Beard, K. H., Cutler, A., Hess, K. T., Gibson, J., and Lawler, J. J. 2007. Random Forest for Classification in Ecology. Ecology, 88: 2783–2792.

Dagorn, L., and Fréon, P. 1999. Tropical tuna associated with floating objects: a simulation study of the meeting point hypothesis. Can J Fish Aquat Sci, 56: 984–993.

Dagorn, L., Holland, K. N., Restrepo, V., and Moreno, G. 2013a. Is it good or bad to fish with FADs? What are the real impacts of the use of drifting FADs on pelagic marine ecosystems? Fish and Fisheries, 14: 391–415.

Dagorn, L., Bez, N., Fauvel, T., and Walker, E. 2013b. How much do fish aggregating devices (FADs) modify the floating object environment in the ocean? Fisheries Oceanography, 22: 147–153.

Dale, M. R. T., and Fortin, M.-J. 2009. Spatial autocorrelation and statistical tests: Some solutions. Journal of Agricultural, Biological, and Environmental Statistics, 14: 188–206.

Davies, T. K., Martin, S., Mees, C., Chassot, E., and Kaplan, D. M. 2012. A review of the conservation benefits of marine protected areas for pelagic species associated with fisheries. ISSF Technical Report 2012-

02. International Seafood Sustainability Foundation, McLean, Virginia, USA.

Davies, T. K., Mees, C. C., and Milner-Gulland, E. J. 2014. The past, present and future use of drifting fish aggregating devices (FADs) in the Indian Ocean. Marine Policy, 45: 163–170.

Davies, T. K., Mees, C. C., and Milner-Gulland, E. J. 2015. Second-guessing uncertainty: Scenario planning for management of the Indian Ocean tuna purse seine fishery. Marine Policy, 62: 169–177.

Delgado de Molina, A., Floch, L., Rojo, V., Damiano, A., Ariz, J., Chassot, E., N'Gom, F., et al. 2014. Statistics of the European and associated purse seine and baitboat fleets in the Atlantic Ocean. Collect. Vol. Sci. Pap. ICCAT, SCRS/2013/149. ICCAT.

Delgado de Molina, A., Ariz, J., Murua, H., Santana, J. C., Ramos, L., and Soto, M. 2014. Spanish Fish Aggregating Device Management Plan. Preliminary data in the Indian Ocean. IOTC-2014-WPTT16-19.

Dempster, T., and Taquet, M. 2004. Fish aggregation device (FAD) research: gaps in current knowledge and future directions for ecological studies. Reviews in Fish Biology and Fisheries, 14: 21–42.

Dickey-Collas, M., Nash, R. D., Brunel, T., Van Damme, C. J., Marshall, C. T., Payne, M. R., Corten, A., et al. 2010. Lessons learned from stock collapse and recovery of North Sea herring: a review. ICES Journal of Marine Science: Journal du Conseil: fsq033.

Dreiseitl, S., and Ohno-Machado, L. 2002. Logistic regression and artificial neural network classification models: a methodology review. Journal of Biomedical Informatics, 35: 352–359.

Eckert, R. D. 1979. The enclosure of ocean resources: economics and the Law of the Sea. Stanford, Calif.: Hoover Institution Press.

Engelhard, G. H. 2009. One hundred and twenty years of change in fishing power of English North Sea trawlers. Advances in fisheries science, 50: 1–25.

Escalle, L., Capietto, A., Chavance, P., Dubroca, L., Molina, A. D. D., Murua, H., Gaertner, D., et al. 2015. Cetaceans and tuna purse seine fisheries in the Atlantic and Indian Oceans: interactions but few mortalities. Marine Ecology Progress Series, 522: 255–268.

FAO. 2014. The State of World Fisheries and Aquaculture 2014. Challenges and opportunities. FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, Rome. http://www.fao.org/3/a-i3720e/index.html (Accessed 13 February 2016).

Filmalter, J. D., Capello, M., Deneubourg, J.-L., Cowley, P. D., and Dagorn, L. 2013. Looking behind the curtain: quantifying massive shark mortality in fish aggregating devices. Frontiers in Ecology and the Environment, 11: 291–296.

Fischer, J., Jorgensen, J., Josupeit, H, Kalikoski, D., and Lucas, C.M. 2015. Fishers' knowledge and the ecosystem approach to fisheries: applications, experiences and lessons in Latin America. FAO Fisheries and Aquaculture Technical Paper No. 591. FAO, Rome.

Floch, L., Chassot, E., Damiano, A., Fonteneau, A., Kouassi, Y., Cauquil, P., Amandè, J. M., et al. 2012a. Statistics of the French purse seine fleet targeting tropical tuna in the Atlantic Ocean (1991-2010). Vol.Sci. Pap. ICCAT, 68(3).

Floch, L., Delgado de Molina, A., Assan, C., Areso, J.-J., and Chassot, E. 2012b. Statistics of the European purse seine fishing fleet and assoc iated flags targeting tropical tunas in the Indian Ocean (1981-201 1). Proceedings of the 14 th Session of the IOTC Working Party on Tropical Tunas: 14–22.

Fonteneau, A. 2015. On the recent steady decline of skipjack caught by purse seiners in free schools in the eastern Atlantic and Western Indian oceans. Collect. Vol. Sci. Pap. ICCAT, 71: 417–425.

Fonteneau, A., and Chassot, E. 2014. Managing tropical tuna fisheries through limiting the number of drifting fish aggregating devices in the Indian Ocean: food for thought. IOTC-2014-WPTT16-22. IOTC.

Fonteneau, A., Chassot, E., and Bodin, N. 2013a. Global spatio-temporal patterns in tropical tuna purse seine fisheries on drifting fish aggregating devices (DFADs): Taking a historical perspective to inform current challenges. Aquatic Living Resources, 26: 37–48.

Fonteneau, A., Gaertner, D, Maufroy, A., and Amandè J.. 2015. Effects of the ICCAT FAD moratorium on the FAD tuna fisheries and tuna stocks. ICCAT Vol Sci, SCRS/2015/162.

Fonteneau, A., Pallares, P., and Pianet, R. 2000a. A worldwide review of purse seine fisheries on FADs. In Pêche thonière et dispositifs de concentration de poissons., pp. 15–35. Le Gal, J.Y., Cayré, P., and Taquet, M.

Fonteneau, A., Ariz, J., Gaertner, D., Nordstrom, V., and Pallares, P. 2000b. Observed changes in the species composition of tuna schools in the Gulf of Guinea between 1981 and 1999, in relation with the Fish Aggregating Device fishery. Aquatic Living Resources, 13: 253–257.

Fonteneau, A., Gaertner, D., and Nordström, V. 1999. An overview of problems in the CPUE - abundance relationship for the tropical purse seine fisheries. In Meeting of the ICCAT working group on tropical tuna abundance indices, pp. 259–276. Ed. by Meeting of the ICCAT Working Group on Tropical Tuna Abundance Indices

Fonteneau, A. 1997. Atlas des pêcheries thonières tropicales: captures mondiales et environnement. ORSTOM éditions. 180 pp.

Fossette, S., Witt, M. J., Miller, P., Nalovic, M. A., Albareda, D., Almeida, A. P., Broderick, A. C., et al. 2014. Pan-Atlantic analysis of the overlap of a highly migratory species, the leatherback turtle, with pelagic longline fisheries. Proceedings of the Royal Society of London B: Biological Sciences, 281: 20133065.

Franco, J., Moreno, G., López, J., and Sancristobal, I. 2012. Testing new designs of Drifting Fish Aggretating Device (DFAD) in the Eastern Atlantic to reduce turtle and shark mortality. Collect. Vol. Sci. Pap. ICCAT, 68: 1754–1762.

Fréon, P., and Dagorn, L. 2000. Review of fish associative behaviour: Toward a generalisation of the meeting point hypothesis. Reviews in Fish Biology and Fisheries, 10: 183–207.

Fromentin, J.-M. 2010. The Fate of Atlantic Bluefin Tuna. Science, 327: 1325–1326.

Fulton, E. A., Smith, A. D. M., Smith, D. C., and van Putten, I. E. 2011. Human behaviour: the key source of uncertainty in fisheries management. Fish and Fisheries, 12: 2–17.

Gaertner, D., Ariz, J., Bez, N., Clermidy, S., Moreno, G., Murua, H., and Soto, M. 2016. Catch, Effort, and eCOsystem impacts of FAD-fishing" (CECOFAD) - Final Report.

Gaertner, D., Ménard, F., Develter, C., Ariz, J., and Delgado de Molina, A. 2002. Bycatch of billfishes by the European tuna purse seine-fishery in the Atlantic Ocean. Fisheries Bulletin, 100: 683–689.

Gaertner, D., and Pallares, P. 2002. The European Union Research Project, Efficiency of Tuna Purse-Seiners and Effective Effort (ESTHER): Scientific report of project. Doc. SCTB15-FTWG-3.

Gaertner, D., Ariz, J., Hallier, J.-P., Herrera Armas, M. A., and ICCAT Skipjack Tuna Stock Assessment Session = Réunion ICCAT d'Evaluation des Stocks de Listao = Sesion ICCAT de Evaluacion de Stocks de Listao, Funchal (PRT), 1999/06/29 ; 1999/07/02. 2000. Le point de vue des pêcheurs thoniers à la senne sur l'augmentation des prises de patudo dans l'Atlantique Est et sur les conditions d'utilisation du sonar. In Detailed report on skipjack tuna : report of the ICCAT skipjack assessment session , pp. 553–570. ICCAT, Madrid.

Garcia, S. M. 2003. The ecosystem approach to fisheries: issues, terminology, principles, institutional foundations, implementation and outlook. Food & Agriculture Org.

Gascuel, D., Fonteneau, A., and Foucher, E. 1993. Analyse de l'évolution des puissances de pêche par l'analyse des cohortes : application aux senneurs exploitant l'albacore (Thunnus albacares) dans l'Atlantique Est. Aquatic Living Resources, 6: 15–30.

Geyer, C. J., and Johnson, L. T. 2015. mcmc: Markov Chain Monte Carlo. R package version 0.9-4. http://CRAN.R-project.org/package=mcmc.

Gillet, R. 2007. A short history of industrial fishing in the Pacific Islands. RAP Publication (FAO).

Gilman, E. L. 2011. Bycatch governance and best practice mitigation technology in global tuna fisheries. Marine Policy, 35: 590–609.

Goujon, M., Claude, A., Le Couls, S., and Mangalo, C. 2015. Premier bilan du plan de gestion des DCP mis en place par la France en Océan Atlantique. Collect. Vol. Sci. Pap. ICCAT, 71(1).

Graham, N. A. J., Pratchett, M. S., McClanahan, T. R., and Wilson, S. K. 2013. The Status of Coral Reef Fish Assemblages in the Chagos Archipelago, with Implications for Protected Area Management and Climate Change. In Coral Reefs of the United Kingdom Overseas Territories, pp. 253–270. Ed. by C. R. C. Sheppard. Springer Netherlands.

Grande, M., Murua, H., Zudaire, I., Goñi, N., and Bodin, N. 2014. Reproductive timing and reproductive capacity of the Skipjack Tuna (Katsuwonus pelamis) in the western Indian Ocean. Fisheries Research, 156: 14–22.

Greboval, D., and Munro, G. 1999. Overcapitalization and excess capacity in world fisheries: underlying economics and methods of control. FAO Fisheries Technical Paper (FAO).

Greenblatt, P. R. 1979. Associations of tuna with flotsam in the eastern tropical Pacific. Fish. Bull, 77: 147–155.

Greenpeace France. 2014. Classement des marques de thon en boite - Campagne Arrêthon.

Grzybowski, D. M., Deitch, J. M., Dwyer, S. E., and Eichhorn, D. S. 1995. Historical Perspective Leading up to and Including the United Nations Conference on Straddling Fish Stocks and Highly Migratory Fish Stocks, A. Pace. Envtl. L. Rev., 13: 49.

Guillotreau, P., Salladarré, F., Dewals, P., and Dagorn, L. 2011. Fishing tuna around Fish Aggregating Devices (FADs) vs free swimming schools: Skipper decision and other determining factors. Fisheries Research, 109: 234–242.

Gutiérrez, N. L., Hilborn, R., and Defeo, O. 2011. Leadership, social capital and incentives promote successful fisheries. Nature, 470: 386–389.

Hall, M. A. 1998. An ecological view of the tuna--dolphin problem: impacts and trade-offs. Reviews in Fish Biology and Fisheries, 8: 1–34.

Hall, M. A., Alverson, D. L., and Metuzals, K. I. 2000. By-Catch: Problems and Solutions. Marine Pollution Bulletin, 41: 204–219.

Hall, M., and Roman, M. 2013. Bycatches and non-tuna catches in the tropical tuna purse seine fisheries of the world. FAO Fisheries and Aquaculture Technical Paper, 568. IATTC, Rome.

Hallier, J., and Gaertner, D. 2008. Drifting fish aggregation devices could act as an ecological trap for tropical tuna species. Marine Ecology Progress Series, 353: 255–264.

Hallier, J.-P. 1988. Pêche à la senne dans l'océan Indien : la pêcherie, ses implantations, ses répercussions locales, son suivi scientifique.

Hallier, J.-P. 1995. Tropical tuna fishing with purse seine and log. Infofish International: 53–58.

Hallier, J.-P., Parajua, J. I., and International Workshop on Fishing for Tunas Associated with Floating Objects, La Jolla (USA), 1992/02/11-14. 1992. Review of tuna fisheries on floating objects in the Indian Ocean. In Fishing for tunas associated with floating objects. IATTC, La Jolla.

Hannesson, R. 1996. Fisheries mismanagement: the case of the North Atlantic cod. Fishing News Books Ltd.

Hardin, G. 1968. The Tragedy of the Commons. Science, 162: 1243–1248.

Hilborn, R., and Ledbetter, M. 1985. Determinants of catching power in the British Columbia salmon purse seine fleet. Canadian Journal of Fisheries and Aquatic Sciences, 42: 51–56.

Hilborn, R., and Walters, C. J. 1992. Quantitative fisheries stock assessment: choice, dynamics and uncertainty. Reviews in Fish Biology and Fisheries, 2: 177–178.

Hilborn, R. 2007. Moving to sustainability by learning from successful fisheries. AMBIO: A Journal of the Human Environment, 36: 296–303.

Hutchings, J. A. 2000. Collapse and recovery of marine fishes. Nature, 406: 882–885.

Huxley, T. H. 1883. Inaugural Address. London.

ICCAT. 2015. Report of the Standing Committee on Research and Statistics. September 28 to October 2, 2015. Madrid, Spain.

ICCAT. 2014. Recommandation 14-01 Recommendation by ICCAT on a multi-annual conservation and management program for tropical tunas.

IOTC. 2015. Report of the 17th session of the IOTC Working Party on Tropical Tunas. IOTC-2015-WPTT17-R[E]. Montpellier, France, 23–28 October 2015.

IOTC. 2013. Resolution 13/08 Procedures on a fish aggregating devices (FADs) management plan, including more detailed specification of catch reporting from FAD sets, and the development of improved FAD designs to reduce the incidence of entanglement of non-target species.

IOTC. 2012. Procedures on a Fish Aggregating Devices (FADs) Management Plan. IOTC Resolution, IOTC Resolution, 12/08. Indian Ocean Tuna Commission.

ISSF. 2012a. Report of the 2012 ISSF Stock Assessment Workshop: Understanding Purse Seine CPUE. ISSF Technical Report. Rome, Italy, July 16-19.

ISSF. 2012b. ISSF guide for non-entangling FADs. http://iss-foundation.org/2012/10/18/non-entangling-fads/.

ISSF. 2014. Report of the ISSF Workshop on FADs as Ecological Traps. 29 -31 January 2014, Sète, France.

ISSF. 2016. ISSF tuna stocks status update. Status for the World Fisheries For Tuna.

Itano, D., Fukofuka, S., and Brogan, D. 2004. The development, design and recent status of anchored and drifting FADs in the WCPO.

Itano, D. G. 2002. Super superseiner. In 15th Meeting of the Standing Comité on Tuna and Billfish. SCTS.

Jaquemet, S., Potier, M., and Ménard, F. 2011. Do drifting and anchored Fish Aggregating Devices (FADs) similarly influence tuna feeding habits? A case study from the western Indian Ocean. Fisheries Research, 107: 283–290.

Jennings, S., Kaiser, M., and Reynolds, J. D. 2009. Marine fisheries ecology. John Wiley & Sons.

Jentoft, S., and McCay, B. 1995. User participation in fisheries management: lessons drawn from international experiences. Marine Policy, 19: 227–246.

Jentoft, S., McCay, B. J., and Wilson, D. C. 1998. Social theory and fisheries co-management. Marine Policy, 22: 423–436.

Johannes, R. E., Freeman, M. M. R., and Hamilton, R. J. 2000. Ignore fishers' knowledge and miss the boat. Fish and Fisheries, 1: 257–271.

Johannes, R., and Neis, B. 2007. The value of anecdote. Fishers' knowledge in fisheries science and management. Coastal Management Sourcebooks, 4: 41–58.

Joseph, J. 2003. Managing fishing capacity of the world tuna fleet.

Jiménez-Valverde, A. 2012. Insights into the area under the receiver operating characteristic curve (AUC) as a discrimination measure in species distribution modelling. Global Ecology and Biogeography, 21: 498–507.

Joo, R., Bertrand, S., Tam, J., and Fablet, R. 2013. Hidden Markov models: the best models for forager movements?

Joseph, J. 2003. Managing fishing capacity of the world tuna fleet.

Joyner, C. C., and von Gustedt, A. A. 1996. The turbot war of 1995: lessons for the law of the sea. The International Journal of Marine and Coastal Law, 11: 425–458.

Juan-Jordá, M. J., Mosqueira, I., Freire, J., and Dulvy, N. K. 2015. Population declines of tuna and relatives depend on their speed of life. In Proc. R. Soc. B, p. 20150322. The Royal Society.

Kaitala, V., and Munro, G. R. 1993. The management of high seas fisheries. Marine Resource Economics: 313–329.

Kaplan, D. M., Chassot, E., Amandé, J. M., Dueri, S., Demarcq, H., Dagorn, L., and Fonteneau, A. 2014. Spatial management of Indian Ocean tropical tuna fisheries: potential and perspectives. ICES Journal of Marine Science: fst233.

Kedziora, D. 1997. Gunboat Diplomacy in the Northwest Atlantic: The 1995 Canada-EU Fishing Dispute and the United Nations Agreement on Straddling and High Migratory Fish Stocks. Northwestern Journal of International Law & Business, 17: 1132.

Kellner, J. B., Tetreault, I., Gaines, S. D., and Nisbet, R. M. 2007. Fishing the line near marine reserves in single and multispecies fisheries. Ecological Applications, 17: 1039–1054.

Kimura, D. K. 1981. Standardized measures of relative abundance based on modelling log (c.p.u.e.), and their application to Pacific ocean perch (Sebastes alutus). Journal du Conseil, 39: 211–218.

Koldewey, H. J., Curnick, D., Harding, S., Harrison, L. R., and Gollock, M. 2010. Potential benefits to fisheries and biodiversity of the Chagos Archipelago/British Indian Ocean Territory as a no-take marine reserve. Marine Pollution Bulletin, 60: 1906–1915.

Kuhn, M. 2008. Building Predictive Models in R Using the caret Package. J Stat Softw: 1–26.

Lackey, R. T. 2005. Fisheries: History, Science, and Management. In Water Encyclopedia. John Wiley & Sons, Inc. http://onlinelibrary.wiley.com/doi/10.1002/047147844X.sw249/abstract (Accessed 12 February 2016).

Lee, J. W., Lee, J. B., Park, M., and Song, S. H. 2005. An extensive comparison of recent classification tools applied to microarray data. Computational Statistics & Data Analysis, 48: 869–885.

Le Gall, J. 2000. Contribution des DCP fixes et derivants a l'accroissement de la puissance de peche des navires de peche thoniere. In Pêche thonière et dispositifs de concentration de poissons, Caribbean-Martinique, 15-19 Oct 1999.

Le Manach, F., Andriamahefazafy, M., Harper, S., Harris, A., Hosch, G., Lange, G.-M., Zeller, D., et al.

2013. Who gets what? Developing a more equitable framework for EU fishing agreements. Marine Policy, 38: 257–266.

Liaw, A., and Wiener, M. 2002. Classification and Regression by randomForest. R News, 2: 18–22.

Lear, W. H. 1998. History of fisheries in the Northwest Atlantic: the 500-year perspective. Journal of Northwest Atlantic Fishery Science, 23: 41–74.

Lennert-Cody, C. E., and Hall, M. 2000. The development of the purse seine fishery on drifting Fish Aggregating Devices in the eastern Pacific Ocean: 1992-1998. In Pêche thonière et dispositifs de concentration de poissons, Caribbean-Martinique, 15-19 Oct 1999 15-19 octobre 1999.

Lodge, M., Anderson, D., Lobach, T., Munro, G., Sainsbury, K., and Willock, A. 2007. Recommanded Best Practices for Regional Fisheries Management Organizations. Report of an Independent Panel to Develop a Model for Improved Governance by Regional Fisheries Management Organizations. Chatham House (London). 160 pp.

Lopez, J., Moreno, G., Sancristobal, I., and Murua, J. 2014. Evolution and current state of the technology of echo-sounder buoys used by Spanish tropical tuna purse seiners in the Atlantic, Indian and Pacific Oceans. Fisheries Research, 155: 127–137.

Lorentzen, T., and Hannesson, R. 2004. The collapse of the Norwegian herring fisheries in the late 1950s and 60s: crisis, adaptation, and recovery.

Mackinson, S. 2001. Integrating local and scientific knowledge: an example in fisheries science. Environmental Management, 27: 533–545.

Marsac, F., Fonteneau, A., and Ménard, F. 2000. Drifting FADs used in tuna fisheries: an ecological trap? In Pêche thonière et dispositifs de concentration de poissons, Caribbean-Martinique, 15-19 Oct 1999.

Marsac, F., Fonteneau, A., and Michaud, P. 2014. L'or bleu des Seychelles. L'histoire de la pêche industrielle au thon dans l'océan Indien. IRD Editions, Marseille, France. 271 pp.

Marsac, F., and Stéquert, B. 1983. Premiers résultats de la prospection du thonier senneur 'Yves de Kerguelen' dans l'océan Indien. La Pêche Maritime, 62: 458–465.

Marsac, F., and Stéquert, B. 1984. Bilan des prospections sur les ressources thonières de surface effectuées depuis 1971 dans l'océan Indien occidental. Pêche Maritime: 1–12.

Maufroy, A., Chassot, E., Joo, R., and Kaplan, D. M. 2015. Large-scale examination of spatio-temporal patterns of drifting fish aggregating devices from tropical tuna fisheries of the Indian and Atlantic Oceans. PLoS ONE.

Marchal, P., Andersen, B., Caillart, B., Eigaard, O., Guyader, O., Hovgaard, H., Iriondo, A., et al. 2007. Impact of technological creep on fishing effort and fishing mortality, for a selection of European fleets. ICES Journal of Marine Science: Journal du Conseil, 64: 192–209.

Marchal, P., Nielsen, J. R., Hovgård, H., and Lassen, H. 2001. Time changes in fishing power in the Danish cod fisheries of the Baltic Sea. ICES Journal of Marine Science: Journal du Conseil, 58: 298–310.

Martin, S., Mees, C., Edwards, C., and Nelson, N. 2011. A preliminary investigation into the effects of Indian Ocean MPAs on yellowfin tuna, Thunnus albacares, with particular emphasis on the IOTC closed area. SC14-40[E]. IOTC Sientific Committee, Mahé, Seychelles. http://www.iotc.org/files/proceedings/2011/sc/IOTC-2011-SC14-40%5BE%5D.pdf (Accessed 6 March 2012).

Maunder, M. N., and Punt, A. E. 2004. Standardizing catch and effort data: a review of recent approaches. Fisheries Research, 70: 141–159.

Ménard, F., Fonteneau, A., Gaertner, D., Nordstrom, V., Stéquert, B., and Marchal, E. 2000a. Exploitation of small tunas by a purse-seine fishery with fish aggregating devices and their feeding ecology in an eastern tropical Atlantic ecosystem. ICES Journal of Marine Science: Journal du Conseil, 57: 525–530.

Ménard, F., Stéquert, B., Rubin, A., Herrera, M., and Marchal, É. 2000b. Food consumption of tuna in the Equatorial Atlantic ocean: FAD-associated versus unassociated schools. Aquatic Living Resources, 13: 233–240.

Meynard, C. N., and Kaplan, D. M. 2013. Using virtual species to study species distributions and model performance. Journal of Biogeography, 40: 1–8.

Miyake, M., Guillotreau, P., Sun, C.-H., and Ishimura, G. 2010. Recent developments in the tuna industry: stocks, fisheries, management, processing, trade and markets. FAO Fisheries and Aquaculture Technical Paper, No.543. FAO, Rome. http://www.fao.org/docrep/013/i1705e/i1705e.pdf.

Miyake, M., Miyabe, N., Nakano, H., and Nations, F. and A. O. of the U. 2004. Historical Trends of Tuna Catches in the World. Food & Agriculture Org. 84 pp.

Moulton, B. R. 1986. Random group effects and the precision of regression estimates. Journal of Econometrics, 32: 385–397.

Moreno, G., Dagorn, L., Sancho, G., Garcia, D., and Itano, D. 2007. Using local ecological knowledge (LEK) to provide insight on the tuna purse seine fleets of the Indian Ocean useful for management. Aquatic Living Resources, 20: 367–376.

Morón, J. 2007. Tuna fishing capacity: perspective of the purse-seine fishing industry on factors affecting it and its management. In Methodological Workshop on the Management of Tuna Fishing Capacity: Stock Status, Data Envelopment Analysis, Industry Surveys and Management Options. La Jolla, California, United States of America. FAO Fisheries Proceedings, pp. 117–127.

Morón, J., Areso, J., and Pallarés, P. 2001a. Statistics and technical information about the Spanish purse-seine fleet in the Pacific. 14th Standing Committee on Tuna and Billfish. Working Paper FTWG-11.

Morón, J., Areso, J., and Pallarés, P. 2001b. Statistics and technical in- formation about the Spanish purse-seine fleet in the Pacific. 14th Standing Committee on Tuna and Billfish, Working Paper FTWG-11.

Munro, G., and Sumaila, U. R. 2002. The impact of subsidies upon fisheries management and sustainability: the case of the North Atlantic. Fish and Fisheries, 3: 233–250.

Murtagh, F., and Legendre, P. 2014. Ward's hierarchical agglomerative clustering method: which algorithms implement Ward's criterion? Journal of Classification, 31: 274–295.

Myers, R. A., Hutchings, J. A., and Barrowman, N. J. 1997. Why Do Fish Stocks Collapse? The Example of Cod in Atlantic Canada. Ecological Applications, 7: 91–106.

Myers, R. A., and Worm, B. 2003. Rapid worldwide depletion of predatory fish communities. Nature, 423: 280–283.

Neis, B., Schneider, D. C., Felt, L., Haedrich, R. L., Fischer, J., and Hutchings, J. A. 1999. Fisheries assessment: what can be learned from interviewing resource users? Canadian Journal of Fisheries and Aquatic Sciences, 56: 1949–1963.

Nicodemus, K. K., Malley, J. D., Strobl, C., and Ziegler, A. 2010. The behaviour of random forest permutation-based variable importance measures under predictor correlation. BMC Bioinformatics, 11: 110.

O'Neill, M. F., and Leigh, G. M. 2007. Fishing power increases continue in Queensland's east coast trawl fishery, Australia. Fisheries Research, 85: 84–92.

OECD. 2006. Financial support to fisheries: implications for sustainable development. OECD Publishing.

Olson, D. B., Hitchcock, G. L., Mariano, A. J., Ashjian, C. J., Peng, G., Nero, R. W., and Podesta, G. P.

1994. Life on the edge: marine life and fronts. Oceanography, 7: 52–60.

Pallares, P., Mina, X., de Molina, A. D., Artetxe, I., Ariz, J., and Arrizabalaga, H. 2002. Análisis de la actividad de los buques auxiliares en el Océano Atlántico y su efecto sobre el rendimiento de atuneros congeladores.

Pauly, D., Alder, J., Bennett, E., Christensen, V., Tyedmers, P., and Watson, R. 2003. The Future for Fisheries. Science, 302: 1359–1361.

Pauly, D., Christensen, V., Dalsgaard, J., Froese, R., and Torres, F. 1998. Fishing down marine food webs. Science, 279: 860–863.

Pauly, D., Christensen, V., Guénette, S., Pitcher, T. J., Sumaila, U. R., Walters, C. J., Watson, R., et al. 2002. Towards sustainability in world fisheries. Nature, 418: 689–695.

Philander, S. G. 2001. Atlantic Ocean Equatorial Currents. In Ocean Currents: A Derivative of the Encyclopedia of Ocean Sciences, p. 54:58. Academic Press.

Phillips, S. J., Dudík, M., Elith, J., Graham, C. H., Lehmann, A., Leathwick, J., and Ferrier, S. 2009. Sample selection bias and presence-only distribution models: implications for background and pseudo-absence data. Ecological Applications, 19: 181–197.

Pikitch, E. K., Santora, C., Babcock, E. A., Bakun, A., Bonfil, R., Conover, D. O., Dayton, P., et al. 2004. Ecosystem-Based Fishery Management. Science, 305: 346–347.

Picaut, J. 1984. Major dynamics affecting the eastern tropical Atlantic and Pacific oceans. California Cooperative Oceanic Fisheries Investigations, Progress Report, 25: 41.

Pomeroy, R. S., and Berkes, F. 1997. Two to tango: the role of government in fisheries co-management. Marine policy, 21: 465–480.

Postel, E. 1965. Les thoniers congélateurs français dans l'Atlantique africain. Cahiers ORSTOM.Série Océanographie, 3: 19–62.

R Core Team. 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org.

Ramos, M. L., Delgado de Molina, A., and Ariz, J. 2010. Analysis of activity data obtained from supply vessels' logbooks implemented by the Spanish fleet and associated in Indian Ocean. IOTC -2010-WPTT-22: 13p.

Ravier, C., and Fromentin, J.-M. 2001. Long-term fluctuations in the eastern Atlantic and Mediterranean bluefin tuna population. ICES Journal of Marine Science: Journal du Conseil, 58: 1299–1317.

Reid, C., Kirkley, J. E., Squires, D., and Ye, J. 2005. An analysis of the fishing capacity of the global tuna purse-seine fleet. In Second Meeting of the Technical Advisory Committee of the FAO Project Management of Tuna Fishing Capacity: Conservation and Socio-economics. FAO Fish. Proc, pp. 117–156.

Renard, D., Bez, N., Desassis, N., Beucher, H., Ors, F., and Laporte, F. 2016. RGeostats: The Geostatistical package [Version:11.0.1]. MINES ParisTech. Free download from: http://cg.ensmp.fr/rgeostats.

Royce, W. F. 1988. Centennial Lecture IV: The historical development of fishery science and management. Marine Fisheries Review, 50: 30–40.

Sætre, R., and Da Silva, A. J. 1984. The circulation of the Mozambique channel. Deep Sea Research Part A. Oceanographic Research Papers, 31: 485–508.

Sáenz-Arroyo, A., and Roberts, C. M. 2008. Consilience in fisheries science. Fish and Fisheries, 9: 316–327.

Santiago, J., Lopez, J., Moreno, G., Murua, H., Quincoces, I., and Soto, M. 2015. Towards a Tropical Tuna

Buoy-derived Abundance Index (TT-BAI). SCRS/2015/90.

Santos, A. M. P. 2000. Fisheries oceanography using satellite and airborne remote sensing methods: a review. Fisheries Research, 49: 1–20.

Sardenne, F., Ménard, F., Degroote, M., Fouché, E., Guillou, G., Lebreton, B., Hollanda, S. J., et al. 2015. Methods of lipid normalization for multi-tissue stable isotope analyses in tropical tuna. Rapid Communications in Mass Spectrometry, 29: 1253–1267.

Saulnier, E. 2014. Dynamique spatio-temporelle de l'effort de pêche sur DCP des thoniers senneurs français dans l'océan indien.

Schaefer, K. M., and Fuller, D. W. 2013. Simultaneous behavior of skipjack (Katsuwonus pelamis), bigeye (Thunnus obsesus), and yellowfin (T. albacares) tunas, within large multi-species aggregations associated with drifting fish aggregating devices (FADs) in the equatorial eastern Pacific Ocean. Marine biology, 160: 3005–3014.

Schaefer, M. B. 1957. Some Considerations of Population Dynamics and Economics in Relation to the Management of the Commercial Marine Fisheries. Journal of the Fisheries Research Board of Canada, 14: 669–681.

Schott, F. A., Xie, S.-P., and McCreary, J. P. 2009. Indian Ocean circulation and climate variability. Reviews of Geophysics, 47.

Schott, F. A., and McCreary Jr., J. P. 2001. The monsoon circulation of the Indian Ocean. Progress in Oceanography, 51: 1–123.

Scott, M. D., Bayliff, W. H., Lennert-Cody, C. E., and Schaefer, K. M. 1992. Proceedings of the International Workshop on the Ecology and Fisheries for Tunas Associated with Floating Objects, February 11–13. Inter-American Tropical Tuna Commission Special Report 11. La Jolla, California.

Sempo, G., Dagorn, L., Robert, M., and Deneubourg, J.-L. 2013. Impact of increasing deployment of artificial floating objects on the spatial distribution of social fish species. Journal of Applied Ecology, 50: 1081–1092.

Shankar, D., Vinayachandran, P. N., and Unnikrishnan, A. S. 2002. The monsoon currents in the north Indian Ocean. Progress in Oceanography, 52: 63–120

Sheppard, C. 2010. Marine protected areas and pelagic fishing: The case of the Chagos Archipelago. Marine Pollution Bulletin, 60: 1899–1901.

Smith, T. D. 2002. A History of Fisheries and Their Science and Management. In Handbook of Fish Biology and Fisheries, pp. 61–83. Ed. by P. J. B. Hart and J. D. Reynolds. Blackwell Science Ltd. http://onlinelibrary.wiley.com/doi/10.1002/9780470693919.ch4/summary (Accessed 21 April 2016).

Stéquert, B., and Marsac, F. 1989. Tropical Tuna: Surface Fisheries in the Indian Ocean. Food & Agriculture Org. 256 pp.

Stretta, J.-M., Delgado de Molina, A., Ariz, J., Domalain, G., Santana, J. C., and Le Gall, J. Y. 1998. Les espèces associées aux pêches thonières tropicales dans l'océan Indien. In Le thon : enjeux et stratégies pour l'océan Indien, pp. 369–386. Ed. by P. Cayré and Conférence Internationale Thonière de Maurice, Port Louis (MUS), 1996/11/27-29. ORSTOM, Paris. http://www.documentation.ird.fr/hor/fdi:010016106 (Accessed 19 May 2014).

Stretta, J.-M., and Slepoukha, M. 1986. Analyse des facteurs biotiques et abiotiques associés aux bancs de thons. In Proceeding of the ICCAT conference on the international skipjack year program , pp. 161–169. Ed. by P. E. K. Symons, P. M. Miyake, G. T. Sakagawa, and ICCAT Conference on the International Skipjack Year Program, Ténérife (ESP), 1983/06/21-29. ICCAT, Madrid. http://www.documentation.ird.fr/hor/fdi:23989 (Accessed 8 March 2016).

Strobl, C., Boulesteix, A.-L., Kneib, T., Augustin, T., and Zeileis, A. 2008. Conditional Variable Importance for Random Forests. BMC Bioinformatics, 9: 1471–2105.

Strobl, C., Hothorn, T., and Zeileis, A. 2009. Party on! A New, Conditional Variable Importance Measure for Random Forests Available in the party Package. The R Journal, 1: 14–17.

Sumaila, U. R., Khan, A. S., Dyck, A. J., Watson, R., Munro, G., Tydemers, P., and Pauly, D. 2010. A bottom-up re-estimation of global fisheries subsidies. Journal of Bioeconomics, 12: 201–225.

Sun, C. L., Yeh, S. Z., Chang, Y. J., Chang, H. Y., and Chu, S. L. 2013. Reproductive biology of female bigeye tuna Thunnus obesus in the western Pacific Ocean. Journal of fish biology, 83: 250–271.

The MathWorks, Inc. 2012. Matlab and Statistics Toolbox Release. Natick, Massachusetts, USA.

Tidd, A. N., Reid, C., Pilling, G. M., and Harley, S. J. 2016. Estimating productivity, technical and efficiency changes in the Western Pacific purse-seine fleets. ICES Journal of Marine Science: Journal du Conseil: fsv262.

Torres-Irineo, E., Gaertner, D., Chassot, E., and Dreyfus-Leon, M. 2014. Changes in fishing power and fishing strategies driven by new technologies : the case of tropical tuna purse seiners in the eastern Atlantic Ocean. Fisheries Research, 155: 10–19.

Torres-Irineo, E., Gaertner, D., de Molina, A. D., and Ariz, J. 2011. Effects of Time-Area Closure on Tropical Tuna Purse-Seine Fleet Dynamics Through Some Fishery Indicators. Aquatic Living Resources, 24: 337–350.

UNCLOS. 1982. United Nations Convention on the Law of the Sea of 10 December 1982.

Venables, W. N., and Ripley, B. D. 2002. Modern Applied Statistics with S. Springer, New York. http://www.stats.ox.ac.uk/pub/MASS4.

Visser, L. E. 2004. Reflections on transdisciplinarity, integrated coastal development, and governance. Challenging Coasts. Transdisciplinary Excursions into Integrated Coastal Zone Development: 23–47.

Walters, C. 2003. Folly and fantasy in the analysis of spatial catch rate data. Canadian Journal of Fisheries and Aquatic Sciences, 60: 1433–1436.

Watson, R. A., Cheung, W. W. L., Anticamara, J. A., Sumaila, R. U., Zeller, D., and Pauly, D. 2013. Global marine yield halved as fishing intensity redoubles. Fish and Fisheries, 14: 493–503.

Worm, B., Barbier, E. B., Beaumont, N., Duffy, J. E., Folke, C., Halpern, B. S., Jackson, J. B., et al. 2006. Impacts of biodiversity loss on ocean ecosystem services. science, 314: 787–790.

Worm, B., Hilborn, R., Baum, J. K., Branch, T. A., Collie, J. S., Costello, C., Fogarty, M. J., et al. 2009. Rebuilding Global Fisheries. Science, 325: 578–585.

Yellen, J. E., Brooks, A. S., Cornelissen, E., Mehlman, M. J., and Stewart, K. 1995. A middle stone age worked bone industry from Katanda, Upper Semliki Valley, Zaire. Science (New York, N.Y.), 268: 553–556.

Zudaire, I., Murua, H., Grande, M., and Bodin, N. 2013. Reproductive potential of yellowfin tuna (Thunnus albacares) in the western Indian Ocean. Fishery Bulletin, 111: 252–264.

Thesis contributions

Conferences and Working Groups

Maufroy A, Chassot E, Kaplan DM. 2013. Impacts of drifting Fish Aggregating Devices (dFADs) on the efficacy of pelagic MPAs: a case study for the Chagos Archipelago MPA and the IOTC time-area closure. IMPAC3; 2013 Oct 21; Marseille, France

Maufroy A, Chassot E, Delgado de Molina A, Murua H, Kaplan DM. 2014. Drifting Fish Aggregating Devices (dFAD) ocean trajectories: consequences for fisher strategies and pelagic ecosystems. Ecology Behavior; 2014 May; Montpellier, France.

Maufroy A, Chassot E, Delgado de Molina A, Murua H, Kaplan DM. Drifting Fish Aggregating Device (dFAD) ocean trajectories and their consequences for fisher “foraging strategies” and pelagic ecosystems. ISEC, 2014 July; Montpellier, France

Chassot, E., Goujon, M., Maufroy, A., Cauquil, P., Fonteneau, A., and Gaertner, D. 2014. The use of artificial fish aggregating devices by the French tropical tuna purse seine fleet: Historical perspective and current practice in the Indian Ocean. IOTC-WPTT16-20-Rev

Maufroy A, Chassot E, Delgado de Molina A, Murua H, Kaplan DM. 2014. How many Fish Aggregating Devices are currently drifting in the Indian Ocean? Combining sources of information to provide a reliable estimate. IOTC WPTT16-21.

Maufroy A, Chassot E, Delgado de Molina A, Murua H, Floch L, Kaplan DM. 2015 Drifting Fish Aggregating Devices (dFADs) of the Atlantic Ocean: how many? SCRS/2015/086. First meeting of the ad hoc working group on FADs, 2015 May; Madrid, Spain

Maufroy A, Chassot E, Delgado de Molina A, Murua H, Floch L, Kaplan DM. Augmentation du nombre de DCP dans les Océans Atlantique et Indien : comment modifie-t-elle l’effort de pêche des thoniers senneurs tropicaux ? Forum de l’AFH, 2015 July ; Montpellier, France

Assan, C., Lucas, J., Maufroy, A., Chassot, E., and Delgado de Molina, A. 2015. Seychelles auxiliary vessels in support of purse seine fishing in the Indian Ocean during 2005-2014. IOTC-WPTT17-41.

Druon J.N., Chassot E., and Maufroy A. Potential habitat of tuna species in the Eastern Tropical Atlantic and Western Indian Oceans: A comparative analysis between FAD-associated and free-swimming schools. IOTC-WPTT17-18

Fonteneau, A., Gaertner, D, Maufroy, A., and Amandè J.. 2015. Effects of the ICCAT FAD moratorium on the FAD tuna fisheries and tuna stocks. ICCAT Vol Sci, SCRS/2015/162.

Maufroy A, Gaertner D., Kaplan D.M., Bez N., Soto M., Assan C., Lucas C. and Chassot E. Evaluating the efficiency of tropical tuna purse seiners in the Indian Ocean: first steps towards a measure of fishing effort. IOTC WPTT17-14-Rev1.

Publications

Maufroy A, Chassot E, Joo R, Kaplan DM. Large-scale examination of spatio-temporal patterns of drifting fish aggregating devices from tropical tuna fisheries of the Indian and Atlantic Oceans. PLoS ONE. 2015.

Maufroy A, Kaplan DM, Bez N, Delgado de Molina A, Murua H, Floch L, Chassot E. Massive increase in the use of Fish Aggregating Devices by purse seine fisheries in the Indian and Atlantic Oceans, ICES Journal of Marine Science, 2017.