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To cite this version:

Lauriane Escalle. Spatio-temporal interactions between whale sharks, cetaceans and tropical tuna purse-seine fisheries, within a conservation perspective, in the Atlantic and Indian Oceans. Animal biology. Université Montpellier, 2016. English. NNT : 2016MONTT125 . tel-01647177

HAL Id: tel-01647177

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Collège Doctoral du Languedoc-Roussillon

THÈSE
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 : Écologie Fonctionnelle et Sciences Agronomiques

Présentée par **Lauriane ESCALLE**

Spatio-temporal interactions between whale sharks, cetaceans and tropical tuna purse-seine fisheries, within a conservation perspective, in the Atlantic and Indian Oceans

Soutenue le 22 septembre 2016 devant le jury composé de

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Abstract

In the frame of the Ecosystem Approach to Fishery (EAF) management, impact of the tropical tuna purse-seine fishery on targeted and incidentally captured species should be investigated. They may include megafauna species, such as sharks, rays, cetaceans, turtles or sea birds, which often are emblematic and vulnerable species. Tropical tuna purse-seiners actively search, at the surface of the sea, for clues indicating the presence of tuna schools (e.g. birds, floating objects, whales, dolphins or whale sharks). In the eastern Atlantic and western Indian Oceans, the main two fishing modes are sets on free swimming tuna schools and schools associated with natural or artificial floating objects, thereafter called Fish Aggregating Device (FAD). However dedicated studies on fishing sets associated with whale sharks and cetaceans are still lacking. The aim of this thesis is therefore, using logbook and scientific onboard observer data, to investigate the spatio-temporal co-occurrences and/or interactions between whale sharks, cetaceans and the tuna purse-seine fishery within an ecosystem conservation perspective. This work underlines that the megafauna/ fishery co-occurrence occurs in specific spatio-temporal strata: i) Gabon to Angola (April–September), ii) the Mozambique Channel (June–September), and iii) East of Seychelles (April–September). As baleen whales and whale sharks are filter feeders, the co-occurrence with the purse-seine fishery was mostly linked to highly productive environments (i.e. using proxys including chlorophyll-a concentration). In addition fishing sets involving megafauna were relatively high before 2000 (up to 20% of the sets), but are nowadays less frequent (∼3 and 1.5% of the sets associated with baleen whales and whale sharks). The purse-seine fishery appears to have a relatively low impact on megafauna species with mortality rates of 1.4% for whale sharks and 5.6% for cetaceans. Whale shark satellite tagging also confirms these results on the longer term, but the low sample size precludes any final conclusion. While dolphins are present in fishing areas, very few interactions with the fishery was detected, which highlights the striking difference with the eastern Pacific Ocean where half the sets are associated with dolphin herds. In addition, the diversity of targeted and bycatch species captured under whale shark and baleen whale sets was also investigated. Whale sharks are principally associated with skipjack and yellowfin (of various sizes) tunas and baleen whales mostly to large yellowfin tuna. In addition, bycatch species associated with these two megafauna groups was relatively low and dominated by the silky shark, and bycatch diversity was close to the one found for free swimming tuna schools. Finally, real and/or simulated encircled megafauna conservation measures or fishing effort management measures (especially FAD moratoria including larger ones) were investigated. The first ones were found to have limited consequences on tuna catch and bycatch. Conversely FAD moratoria had limited impacts on the number of megafauna associated fishing sets, due to the fact that the main spatio-temporal strata of megafauna and FAD sets differ. However larger and longer moratoria could be beneficial for juvenile tuna and some bycatch species. Overall, this thesis has lead to increase the knowledge on megafauna/ fishery interactions, essential in the general framework of setting up an EAF in the tropical tune purse-seine fishery.

Key words whale shark, cetaceans, tuna purse-seine fishery, marine megafauna, accidental catch, pelagic ecosystems.

Résumé

Dans le cadre de l'Approche Ecosystémique des Pêches (AEP), il est nécessaire d'évaluer l'impact de la pêche thonière tropicale à la senne sur les espèces ciblées et sur les espèces accessoires. Parmi ces dernières, les espèces de la mégafaune, telles que des requins, raies, cétacés, tortues, oiseaux marins, sont souvent emblématiques et vulnérables. Les thoniers senneurs tropicaux recherchent activement à la surface de l'eau tout indice de la présence de bancs de thon (e.g. oiseaux, objets flottants, baleines, dauphins ou requins baleines). Dans l'est de l'océan Atlantique et l'ouest de l'océan Indien, les deux modes de pêches principaux sont les captures de thons en bancs libres et celles sur bancs associés à un objet flottant, naturel ou artificiel, rassemblés ici sur sous le terme de dispositif de concentration de poisson (DCP). Les calées associées aux requins baleines et aux cétacés sont toutefois peu étudiées. L'objectif de cette thèse est donc d'analyser les co-occurrences et/ou interactions spatio-temporelles entre requins baleines, cétacés et pêche thonière à la senne, dans une perspective de conservation de l'écosystème. Ce travail, basé sur des données de livres de bord et d'observateurs scientifiques embarqués, a montré que la co-occurrence pêche thonière/ mégafaune se localise dans des strates spatio-temporelles relativement précises: i) du Gabon à l'Angola (avril–septembre), ii) dans le Canal du Mozambique (juin–septembre) et iii) à l'est des Seychelles (avril–septembre). Les baleines et requins baleines étant planctivores, la co-occurrence avec la pêche à la senne est principalement liée à une forte productivité primaire (appréhendée à travers des proxys tels que la concentration en chlorophylle-a). De plus, les calées sur ces deux groupes étaient assez élevées avant 2000 (jusqu'à 20% des calées), et qu'elles sont moins fréquentes aujourd'hui (∼3 et 1,5% des calées associées à des baleines et des requins baleines, respectivement). L'impact de la pêche à la senne sur ces espèces semble relativement faible au regard du taux de mortalité apparente de 1,4% pour les requins baleines et 5,6% pour les cétacés. Des marquages satellites réalisés sur les requins baleines, confirment ces observations sur le plus long terme, mais la taille de l'échantillon limite la formulation de conclusions définitives. Concernant les dauphins, bien que présents sur les zones de pêche, ils interagissent très peu avec celle-ci, soulignant ainsi une différence majeure avec l'océan Pacifique est où ce mode de pêche est majoritaire. La diversité spécifique des espèces cible et accessoire associées aux calées sur mégafaune a également été étudiée. Les requins baleines sont associés aux listaos et à l'albacore (dans une large gamme de tailles), alors que les baleines le sont principalement à de gros albacores. De plus, la capture accessoire associée à ces deux groupes de mégafaune est relativement faible et dominée par le requin soyeux et la diversité spécifique est proche de celle trouvée sous les bancs libres de thons. Enfin les effets de mesures de conservation vis-à-vis de la mégafaune encerclée ou de mesures de gestion de l'effort de pêche, notamment les moratoires sur DCP réelles ou simulées (e.g. moratoires élargis), ont été analysés. Les premières ont eu un effet limité en terme de captures cibles et accessoires, alors que les moratoires impactent peu le nombre de calées associés à la mégafaune, ceci en raison du décalage spatio-temporel des co-occurrences. Cependant des moratoires élargis pourraient être bénéfiques pour les thons juvéniles et certaines espèces associées. Par l'analyse quantitative des interactions entre la pêche thonière à la senne et la mégafaune, cette thèse apporte des connaissances essentielles sur les espèces étudiées dans le cadre de la mise en place d'une AEP, applicable à la pêche thonière tropicale.

Mots clés requins baleines, cétacés, pêche thonière à la senne, mégafaune marine, prises accessoires, écosystèmes pélagiques.

Remerciements

Mes premiers remerciements vont tout naturellement à mes directeurs de thèse: Daniel Gaertner, Pierre Chavance et Bastien Mérigot, pour leur encadrement pendant ces trois ans et pour m'avoir donné la possibilité de réaliser cette thèse. Pierre, tout d'abord, pour ton initiation à la pêche thonière à la senne, ainsi qu'aux bases de données qui m'étaient étrangères avant le début de cette thèse et pour ta disponibilité à répondre à mes nombreuses questions. Daniel, merci d'avoir partagé tes grandes connaissances sur cette pêcherie, incluant des connaissances historiques d'un temps que je ne peux connaitre, et également sur diverses méthodes d'analyses. Et Bastien, merci pour ton initiation à la recherche à proprement parlé, incluant la publication scientifique, et pour tes connaissances méthodologiques et analytiques. En général, ce fut un grand plaisir de travailler avec vous pendant ces trois ans. Merci à vous trois pour de votre implication dans ce projet, de votre soutien et de votre disponibilité, ainsi que pour les possibilités qui m'ont été accordées (embarquement, nombreux groupes de travail et congrès scientifiques, séjours d'accueil à l'étranger).

Je pense qu'ensuite, il est logique de remercier les membres de l'observatoire thonier. En premier lieu pour m'avoir permis d'avoir accès aux données. Mais également pour leur disponibilité face à mes questions, interrogations et leurs aiguillages dans mes raisonnements. Laurent Floch et Pascal Cauquil, merci pour votre initiation aux bases de données et au SQL. Nos discussions m'ont souvent permis de préciser mon raisonnement ou de soulever des points nouveaux. Merci également à Pascal Bach, Alain Damiano, Emmanuel Chassot et Patrice Dewals, respectivement sur Sète, aux Seychelles et à Abidjan, pour vos réactions, également rapides, à mes questions diverses. De même, merci aux scientifiques de l'IEO et de l'AZTI, pour leur collaboration à cette thèse, à travers la disponibilité des données espagnoles, mais également pour nos divers échanges scientifiques.

Je souhaite ensuite remercier les personnes m'ayant permis de réaliser cette expérience unique que fut mon embarquement pour une marée sur un thonier senneur, accompagné du développement de l'expérience de marquage de requins baleines. Merci à Laurent Dagron pour la mise à disposition des marques. Merci à JD Filmalter et Fabien Forget, pour nos

discussions pré- et post-marquages. Merci à Justin Amandé, pour ta disponibilité et ton aide pendant mon séjour à Abidjan, mon embarquement, mais également par la suite pour ton appui technique local et la formation des observateurs. Des remerciements particuliers vont à l'équipage de l'AVEL VOR, pour votre accueil à bord et le partage de votre expérience. Merci de m'avoir remotivée et aidée à changer de stratégie en mer suite à une première tentative de marquage infructueuse. Merci à Joël, capitaine de l' AVEL VOR, pour la liberté accordé à la passerelle et pendant les marquages, ainsi que pour nos discussions. Cette expérience de 50 jours à changer ma vision de ce sujet de thèse.

Je tiens également à remercier tous les membres du jury d'avoir accepté de corriger et juger ce travail, ainsi qu'aux membres des deux comités de thèse, Catherine Aliaume, Jérôme Spitz, Christophe Guinet, Evgeny Romanov et Hervé Demarcq pour leurs conseils et remarques.

De même un grand merci aux membres de l'IATTC, notamment Guillermo Compeán, Martin Hall, Marlon Roman, Kurt Schaeffer, Michael Scott et Ernesto Altimirano.

Je voudrais également remercier Jérome Spitz et Charlie Huveneers, pour vos encadrements respectifs avant cette thèse. Merci de m'avoir donné le gout à la recherche (et de ne pas m'en avoir dégouté). C'est également grâce à vous que je suis arrivée là.

Enfin, merci aux collègues et doctorants Sétois, pour ces trois années passées avec vous. Je ne peux citer tout le monde, mais entre autre, Pablo bien sûr, de l'autre côté du bureau, Elisabeth, Alex, Rob, Fabien, Mariana, JD, Fany, Marion, Victoria, Sonia, Angelee, Nico, Camille, Ines, Jules... et une pensée spéciale pour Tom. Et pour finir, un grand merci à ma famille et mes amis. Mes parents et mes frères, pour votre soutien infaillible. Enfin, merci à ces quelques personnes (qui se reconnaitront) indispensables dans ma vie et qui la rende plus belle.

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Glossary of the principal abbreviations

EPO	Eastern Pacific Ocean
EAO	Eastern Atlantic Ocean
WIO	Western Indian Ocean
WCPO	Western and central Pacific Ocean
tRMFO	Tuna regional fishery management organizations
IATTC	Inter-American Tropical Tuna Commission
ICCAT	International Commission for the Conservation of Atlantic Tunas
IOTC	Indian Ocean Tuna Commission
WCPFC	Western and Central Pacific Fisheries Commission
IRD	Institut de Recherche pour le Développement
IEO	Instituto Español de Oceanografía
NE	North-east monsoon period (December–March)
SW	South-west monsoon period (June–September)
INE	North-east inter-monsoon period (October–November)
ISW	South-west inter-monsoon period (April–May)
FAD	Fish Aggregating Device
IUCN	International union for conservation of nature
CITES	Convention of migratory species of wild animals
IWC	International whaling commission
NGO	Non-governmental organization
EEZ	Economic exclusive zone
MPA	Marine protected area
EU	European Union

Synthèse des travaux en français

1. Contexte et objectifs

De nombreuses activités humaines impactent les espèces de la mégafaune marine Baum *et al.* 2003 Magera *et al.* 2013 Wallace *et al.* 2011). Ces espèces sont ainsi touchées par la pêche en tant qu'espèce cible ou accessoire, la destruction de leurs habitats, la pollution, le trafic maritime, Hoffmann *et al.* 2010). Il est néanmoins globalement reconnu que la pêche représente la majeure menace pour les Read *et al.* 2006 Stevens *et al.* 2000 Wallace *et al.* 2011). Or en majorité ces espèces sont potentiellement très vulnérables à la mortalité par la pêche en raison de leur taux de croissance faibles, d'une Musick *et al.* 2000 Žydelis *et al.* 2009).

Au niveau de l'océan hauturier, les thoniers senneurs tropicaux recherchent activement à la surface de l'eau tout indice indiquant la présence de bancs de thons. Ces indices peuvent être la présence de groupes d'oiseaux, la déformation de la surface de l'eau lié au comportement alimentaire des thons, la présence d'objets flottants (naturels ou artificiels) ou d'espèces de la mégafaune marine (i.e. cétacés ou requins baleines *Rhincodon typus*). En effet, diverses espèces marines, dont les thons tropicaux, ont tendance à s'agréger sous des objets flottants. Certaines espèces de thons peuvent également s'associer, principalement pour s'alimenter sur des proies communes, avec des espèces de la mégafaune marine Hampton and Bailey 1999). Les pêcheurs mettent donc à profit ces comportements pour améliorer leur efficacité de pêche. D'une manière générale lors des évaluations des stocks de thons tropicaux, on distingue différents modes de pêche en fonction du type d'association du banc de thon capturé. Au niveau mondial, les deux principaux modes de pêche sont les captures de thons en bancs libres et celles sur bancs associés à un objet flottant naturel, ou le plus souvent artificiel, appelé Dispositif de Concentration de Poisson (DCP). L'utilisation de ces derniers a subi une forte augmentation depuis les années 1990s, avec notamment

l'apport de nouvelles technologies telles que des balises GPS, permettant de suivre leur déplacement, et récemment d'estimer la quantité de thon agrégé sous le DCP grâce à des Lopez *et al.* 2014). Alors que la pêche sur bancs libres capture principalement de larges individus d'albacore (*Thunnus albacares*) et peu de prises accessoires, la pêche sur DCP capture des petits individus de thons (listaos *Katsuwonus pelamis*, mais également des juvéniles d'albacore et de patudo *Thunnus obesus*) et une plus grande quantité et diversité de prises accessoires. Depuis plusieurs décennies, l'utilisation croissante des DCP a donc suscité de nombreuses préoccupations quant à la soutenabilité des stocks de thons, mais également sur l'impact de cette pratique de pêche sur d'autres espèces jugées vulnérables (e.g. le requin soyeux *Carcharhinus falciformis* Ariz and Gaertner 1999 Hall *et al.* 1999 Hallier and Parajua 1999 Hampton and Bailey 1999). Par ailleurs, dans l'est de l'océan Pacifique, un autre mode de pêche est majoritaire, il s'agit de la capture de bancs de thons associés à des groupes de dauphins. Ceux-ci se retrouvant encerclés dans la senne au même titre que les thons, ce mode pêche a conduit à de très fortes mortalités de dauphins dans les Hall 1998). Enfin, dans tous les océans, des calées sont également Gaertner and Medina-Gaertner 1999 Romanov 2002 Stretta and Slepoukha 1986 WCPFC 2010).

Dans le cadre d'une Approche Ecosystémique des Pêches (AEP), il est nécessaire d'évaluer l'impact de la pêche thonière tropicale à la senne sur les espèces ciblées, mais FAO 2003). Globalement les calées sur bancs libres, sur DCP et sur dauphins (pour le Pacifique est) sont relativement bien suivies et différentes mesures de régulation de l'effort de pêche (i.e. fermeture de zones, moratoire sur DCP) ont déjà été mises en place pour protéger les stocks d'albacore et de patudo. Au contraire, les calées associées aux requins baleines et aux cétacés, sont peu étudiées. Dans l'est de l'océan Atlantique les calées associées aux requins baleines et aux Stretta and Slepoukha 1986). Dans l'ouest de l'océan Indien, ces calées sont également effectuées mais Romanov 2002). De nos jours, les calées associées à la mégafaune sont considérées comme rares dans ces deux océans et sont peu étudiées. Par ailleurs, pour des raisons de gestion des stocks de thons tropicaux, les calées associées aux requins baleines, considérées comme capturant un assemblage d'espèces similaire à celui sur DCP, sont communément assimilées à celles-ci. De même, les calées associées aux baleines sont généralement assimilées aux calées sur bancs libres. Or, le fait que ces espèces soient référencées dans des conventions internationales de conservation des espèces marines (IUCN, CITES) a conduit les organisations régionales de gestion des pêches thonières (ORGPs), ainsi que des organisations non gouvernementales écologistes, à être en demande

d'informations scientifiques sur les interactions pêche à la senne/mégafaune et sur les impact potentiels de cette pêcherie sur les requins baleines et les cétacés. L'objectif de cette thèse est donc d'analyser les interactions (i.e. calées directement effectuées en association ou autour des ces espèces et pouvant conduire à leur capture) et/ou co-occurrences (i.e. présence sur les zones de pêche sans interagir avec celle-ci) spatio-temporelles entre requins baleines, cétacés et pêche thonière à la senne et d'évaluer l'impact de cette pêcherie sur ces espèces, et ce, dans une perspective de conservation de l'écosystème.

Pour répondre à cet objectif, différentes bases de données de la flotte européenne (France, Espagne et pavillons associés) ont été analysées. Il s'agit principalement i) des livres de bord des senneurs rempli par les capitaines depuis les années 1960 dans l'Atlantique et le début des années 1980 dans l'océan Indien et ii) des registres des observateurs scientifiques embarqués à bord des thoniers senneurs à travers différents programmes scientifiques depuis 1995 et de façon continue depuis 2003. Alors que les livres de bords sont remplis systématiquement par tous les capitaines, le taux de couverture des données observateurs, assez faible historiquement (<10%), a augmenté depuis 2014 dans les deux océans (100% dans l'Atlantique et ∼40% dans l'Indien). Malgré cette différence en terme de couverture d'échantillonnage, les observateurs scientifiques enregistrent des informations complémentaires, et plus détaillées, que celles notées par les capitaines. Ainsi ils enregistrent diverses informations liées aux prises accessoires et à la mégafaune encerclée, par exemple le devenir des individus capturés, mais également toute observation de la mégafaune réalisée pendant la journée.

Cette thèse se décline sous la forme de cinq chapitres principaux suivis d'une discussion générale. Les objectifs principaux étant i) de décrire les interactions et/ou co-occurrences spatio-temporelles dans l'est de l'océan Atlantique et l'ouest de l'océan Indien entre la pêche thonière tropicale à la senne et les requins baleines (chapitre 2), et les cétacés (chapitre 3), ii) d'évaluer l'impact de cette pêcherie sur ces espèces de la mégafaune (chapitre 2 et 3), iii) d'étudier le lien entre conditions environnementales et co-occurrences observées entre requins baleines, cétacés et pêche thonière à la senne, iv) de caractériser la composition spécifique et le spectre de taille des espèces cibles, ainsi que la diversité des espèces accessoires capturées en association avec les requins baleines et les cétacés, et v) enfin d'évaluer les conséquences potentielles de mesures de régulation spatio-temporelle de la pêche à la senne (moratoire sous DCP ou fermeture totale à la pêche) et de mesures de conservation de la mégafaune (interdiction d'encerclement des requins baleines et/ou des cétacés) sur les captures cibles et accessoires ainsi que les nombre de calées associées la mégafaune.

2. Interactions entre requins baleines et pêche thonière à la senne dans les océans Atlantique et Indien

A partir de bases constituées des données récoltées depuis les années 1980 par les capitaines et depuis 1995 par les observateurs scientifiques, la co-occurrence et l'interaction spatio-temporelle entre requins baleines et pêche thonière à la senne ont été étudiées. Il a été identifié que les observations de requins baleines sont principalement enregistrées dans ces bases de données lorsqu'ils sont en interaction directe avec la pêcherie, c'est-à-dire lorsqu'ils se retrouvent encerclés dans les filets des senneurs. Ainsi ∼1,5% des calées dans les deux océans se réalisent en association avec des requins baleines (8650 calées enregistrées dans les livres de bord et 180 dans les données observateurs). Les calées sur requins baleines sont en général faites de manière involontaire car le plus souvent ils ne sont pas repérés avant le coup de pêche. Par ailleurs, l'analyse des Observations Par Unité d'Effort (i.e. SPUE) a permis d'identifier que les interactions requins baleines/pêche thonière à la senne se localisent principalement dans des strates spatio-temporelles particulières: i) dans l'océan Atlantique, d'avril à septembre dans la zone côtière du Gabon à l'Angola et ii) dans l'océan Indien, d'avril à mai au niveau du canal du Mozambique. L'impact de la pêche à la senne sur les requins baleines a également été étudié et semble indiquer un taux de mortalité apparente (i.e. au moment de la libération) très faible (1,38%), ce qui correspond à deux cas de mortalité enregistrés sur 145 individus encerclés sur l'ensemble de la période étudiée. La mortalité post-encerclement a ensuite été étudiée sur le plus long terme, grâce au marquage satellite de 6 requins baleines en 2014 dans la strate d'interactions précédemment identifiée dans l'océan Atlantique. Tous les individus ont survécu au moins 21 jours (une marque n'a pas émise de donnée apparemment pour des problèmes lors de la transmission ou une panne de la marque elle-même) ce qui semble confirmer une survie post-encerclement assez élevée mais le faible nombre d'individus marqués limite la formulation de conclusions définitives. Pour combler ce manque, mais également pour suivre le déplacement des individus hors des zones de pêche (suivi pendant six mois), l'opération de marquage est toujours en cours, avec le marquage de 5 individus supplémentaires réalisés en juin 2016. De plus, le développement d'une méthode de marquage spécifique aux requins baleines depuis le pont des thoniers senneurs, ainsi que l'amélioration de la méthode dite de « bonne pratique » de libération des Poisson *et al.* 2014b) ont été détaillées.
Le marquage d'un plus grand nombre d'individus, de toutes tailles y compris de juvéniles, est nécessaire pour estimer la survie post-encerclement et définir, si besoin, des mesures pour atténuer l'impact potentiel de la pêche à la senne sur les population de requins baleines.

3. Interactions entre cétacés et pêche thonière à la senne dans les océans Atlantique et Indien

De la même façon que pour les requins baleines, la co-occurrence et interaction spatio-temporelle entre cétacés et pêche thonière à la senne ont été étudiées dans les océans Atlantique et Indien. La majorité des observations de cétacés implique des baleines qui sont, comme pour les requins baleines, principalement observés pendant les activités de pêches et interagissent également directement avec la pêcherie. Ainsi, dans les deux océans les calées associées aux baleines représentent ∼3% des coups de pêche (14 900 calées enregistrées dans les livres de bord et 450 dans les données observateurs). Les encerclements effectifs sont cependant relativement rares, puisque la plupart du temps les baleines s'échappent d'elles-mêmes du filet en plongeant avant sa fermeture ou bien en passant à travers. Par contre, contrairement aux encerclements de requins baleines, la majorité des calées associées aux baleines sont intentionnelles, puisque celles-ci sont repérées par l'équipage avant le coup de pêche et utilisées comme indicateur de la présence de bancs de thons. Les dauphins ont également été détectés sur les zones de pêche à la senne dans les deux océans. Cependant très peu de calées ont été enregistrées sur des bancs de thons associés à des dauphins (0,05% soit 258 et 85 calées associées à des dauphins dans les livres de bords et les données observateurs). Ceux-ci sont donc considérés comme étant seulement en co-occurrence avec la pêcherie. Cela renforce donc bien la différence entre les océans Atlantique et Indien d'une part et l'océan Pacifique est d'autre part, où des conditions environnementales particulières (thermocline peu profonde, eau de surface chaude et zone de minimum d'oxygène épaisse) conduisent à une association thons-dauphins très fréquente et font qu'environ la moitié des calées sont réalisées sur dauphins. Les SPUE de cétacés ont permis d'identifier des strates spatio-temporelles, dont certaines communes à celles trouvées pour les requins baleines, où les interactions et co-occurrences avec la pêche thonière à la senne sont plus élevées: i) l'est des Seychelles de décembre à mars et ii) le canal du Mozambique d'avril à mai dans l'océan Indien, et iii) la zone côtière du Gabon d'avril à septembre dans l'océan Atlantique. L'impact de la pêche à la senne sur les cétacés est également relativement faible (mortalité apparent de 5,79%), avec la mortalité de huit dauphins tachetés pantropicaux et de trois baleines à bosses enregistrés depuis 1995 dans les données observateurs (∼10% de couverture).

4. Facteurs environnementaux liés aux co-occurrences entre mégafaune et pêche thonière à la senne

Après avoir identifié que les co-occurrences entre les requins baleines, les cétacés et la pêche thonière à la senne se concentraient au niveau de strates spatio-temporelles précises, il est apparu évident de s'interroger quand à un possible lien des conditions environnementales avec ces co-occurrences. En effet, on peut supposer que la distribution de ces espèces de la mégafaune, ainsi que des thons (et donc de la pêche) est directement ou indirectement influencée par certains facteurs, dont la productivité primaire à travers la distribution de leurs proies. Pour valider ces hypothèses des modèles delta, alliant des GAM (modèles additifs généralisés) et des BRT (arbres de régression « stimulés »), ont été réalisés séparément pour les requins baleines et les cétacés dans chaque océan afin d'identifier les principaux facteurs environnementaux liés aux co-occurrences observées avec la pêche à la senne. Dans l'océan Atlantique, la concentration en chlorophylle-a est la variable qui contribue le plus aux modèles des requins baleines et des cétacés (5–6% de déviance expliquée). Alors que dans l'océan Indien, d'autres facteurs associés indirectement à la productivité, telles que l'énergie cinétique des tourbillons et la distance au plateau continental ont été significatifs (3–21%). De plus, dans cet océan les moussons ont également une influence sur les co-occurrences observées (3–4%). Ainsi, nous pouvons conclure que les fortes co-occurrences entre requins baleines, cétacés et pêche thonière à la senne sont principalement observées dans des zones productives de l'océan, ce qui concorde avec le fait que baleines (mysticètes) et requins baleines sont planctivores.

5. Capture cible et accessoire associée aux calées sur requins baleines et baleines

Dans une AEP, il est indispensable de s'intéresser à l'impact de la pêche thonière à la senne sur les espèces cibles, mais également sur les captures accessoires. Après avoir identifié que la pêche thonière à la senne avait un impact (tout du moins apparent) relativement faible sur les requins baleines et les cétacés, il est important de s'intéresser également aux autres espèces associées à la mégafaune encerclée. Ceci permettant également d'évaluer l'impact de la pêche à la senne sur ces associations inter-spécifiques pélagiques. Ainsi, dans le but d'étudier la composition spécifique et le spectre de taille des espèces ciblées et la diversité des espèces accessoires, nous avons utilisé des données provenant des livres de bords, des données observateurs, ainsi que des échantillonnages scientifiques réalisés au débarquement des thoniers senneurs. La diversité et la composition des assemblages

de poissons ont ensuite été quantifiées à l'aide d'indices complémentaires décrivant les principales facettes de la diversité des assemblages (nombre d'espèces et équitabilité) et d'analyses multi-variées. La grande similarité entre les calées associées aux baleines et celles sur bancs libres a pu être validée. En effet ces calées capturent principalement des gros albacores et ont un risque de coup nul assez élevé (70–50%). De plus, des prises accessoires sont présentes dans seulement la moitié des calées positives (i.e. avec capture de thons) et l'assemblage d'espèces accessoires capturé est très proches de celui trouvé sur bancs libres (diversité alpha et béta). Cependant, les calées associées aux baleines capturent en moyenne la plus grande biomasse de thon (29 et 38 t en moyenne, dans les océans Atlantique et Indien) parmi les quatre modes de pêche. Les calées associées aux requins baleines, ont par contre, un statut intermédiaire entre les calées sur DCP et celles sur bancs libres, bien que plus proche des DCP. En effet, la plupart des calées sur requins baleines sont positives et capturent des listaos et des juvéniles d'albacore, mais également de gros individus de cette espèce. Bien que des prises accessoires soient enregistrées dans la majorité des calées, la composition et la diversité spécifique (richesse et équitabilité) des espèces accessoires sont proches de celles trouvées sous les bancs libres de thons. Par ailleurs, la biomasse de capture accessoire associée à ces deux groupes de mégafaune est relativement faible (1–2,6% de la capture de thon en moyenne) et dominée par le requin soyeux (deux taxons par calée en moyenne avec une équitabilité variant entre 0,6 dans l'océan Atlantique et 0,9 dans l'océan Indien). Ces résultats suggèrent que bien que rares, les calées associées aux requins baleines pourraient être classées dans une catégorie à part, notamment du fait de leur différence avec les calées sur DCP en terme de captures accessoires. Il est également important de noter que des espèces vulnérables se retrouvent parmi les plus abondantes dans la capture accessoire de ces modes de pêches (requins soyeux) ou avec une occurrence assez élevée (raies manta).

6. Conséquences de mesures de régulation de l'effort de pêche et de conservation de la mégafaune

L'estimation précise de la composition spécifique et de la taille des espèces cibles, mais également de la quantité et la diversité des espèces accessoires capturées sous les quatre modes de pêche est importante pour des questions de gestion des thons tropicaux, mais également pour l'élaboration des statistiques de pêches. En particulier, cette estimation peut permettre d'évaluer les conséquences, en terme de relocalisation de l'effort de pêche sur d'autres modes de pêche, de mesures de régulation de l'effort de pêche ou de conservation de la mégafaune. En effet, depuis les années 1990s, l'utilisation croissante des DCP dans

les deux océans a conduit à l'instauration de mesures spatio-temporelles de régulation de leur usage, visant principalement à protéger les stocks de juvéniles d'albacore et de patudo. Cependant, la capture élevée d'espèces accessoires sous DCP, ainsi que l'impact collatéral potentiel de ces mesures de régulation sur les autres modes de pêche, devraient également être pris en compte. Pour cela, dans un premier temps les effets d'un report potentiel de l'effort de pêche sur ces deux groupes de la mégafaune, lors de la mise en place de ces mesures dans un passé récent, ont été étudiés par des analyses de type « Before-After ». Dans la mesure où ces réglementations couvraient principalement des strates spatio-temporelles avec peu de calées associées aux baleines et requins baleines, peu d'effets ont été détectés. Dans un deuxième temps des simulations de Monte Carlo, basées sur des données de pêche de la dernière décennie, ont été réalisées pour estimer les conséquences potentielles de moratoires sous DCP «élargis» (à 6 mois et couvrant de plus larges zones que les mesures déjà mises en place). La diminution de la capture de petits thons (<10kg) serait totalement ou partiellement compensée par une augmentation de celle de gros individus (>10kg) et conduirait au final à une diminution des captures totales dans l'océan Indien et à une augmentation dans l'océan Atlantique. Dans le même temps dans l'océan Indien les captures des espèces accessoires diminueraient, et les calées sur requins baleines et baleines augmenteraient légèrement. A l'inverse, dans l'océan Atlantique les conséquences de ces grands moratoires seraient différentes selon les espèces composant les prises accessoires, alors que le nombre de calées associées à la mégafaune resterait stable. Enfin, en parallèle, l'impact des mesures de conservation des requins baleines et de ces cétacés mises en place récemment (e.g. encerclement volontaire interdit dans l'océan Indien) sur les stratégies de pêche (i.e. report de l'effort sur les DCP) et sur les captures cibles et accessoires, n'ont pas été évalués. Dans cet ordre d'idée des simulations de Monte-Carlo ont également été effectuées pour évaluer les conséquences de mesures potentielles d'interdiction spatio-temporelle (i.e. dans les strates précédemment identifiées) de pêcher en association avec les requins baleines et/ou des baleines. Certaines simulations d'interdiction spatio-temporelle de la pêche associée aux requins baleines et aux baleines, particulièrement quand ces deux modes de pêches étaient interdits, ont conduit à une modification des stratégies de pêche. Le nombre de calées sur DCP et sur banc libre a augmenté, les prises accessoires de poissons portes épées et de requins ont légèrement diminué, mais les captures de thons sont restées stables. Ces simulations, basées sur des données de pêche thonière historiques, peuvent donc être un outil utile pour évaluer la pertinence d'une mesure de régulation de l'effort de pêche ou de conservation avant son implémentation tout en tenant compte de potentiels impacts collatéraux.

7. Discussion et conclusion

A travers ce travail de thèse, nous avons pu montrer que dans l'est de l'océan Atlantique et l'ouest de l'océan Indien les interactions entre pêche thonière et mégafaune marine impliquaient principalement les requins baleines et les baleines. Par ailleurs, ces deux modes de pêche se concentraient, dans chaque océan, dans des strates spatio-temporelles précises, liées à des environnements marins à forte productivité primaire (upwelling, embouchures de fleuves, tourbillons). Par ailleurs, l'impact apparent de la pêche thonière sur ces deux groupes d'espèces de la mégafaune semble relativement faible. En complément, la capture d'espèces cibles et accessoires associées aux requins baleines et aux baleines a également été étudiée. Les calées sur baleines sont associées à un assemblage d'espèces très proche de celui trouvé dans les calées sur bancs libres avec de gros albacores accompagnés ou non de peu de prises accessoires. Alors que les calées sur requins baleines sont associées à un assemblage d'espèces plus proche de celui trouvé dans les calées sous DCP pour les thons, mais sans les autres espèces de poissons abondamment associées aux DCP. Enfin les mesures de régulations de l'effort de pêche sous DCP (mesures incluant de larges moratoires) semblent avoir peu d'effets sur le nombre de calées associé à la mégafaune, car elles couvrent des strates spatio-temporelles différentes et il ne semble pas y avoir un report important de l'effort de pêche dans ces strates. Cependant des moratoires élargis pourraient être bénéfiques pour les thons juvéniles et certaines espèces associées. De la même façon, les mesures de conservation vis-à-vis des espèces de la mégafaune ont eu un effet limité sur l'effort de pêche et les captures, de part leur nombre relativement faible de nos jours.

Au niveau des principales strates spatio-temporelles d'interactions avec la pêche thonière, les estimations d'abondance des populations présentes, notamment pour les baleines car celles-ci sont peu connues pour les requins baleines, semblent indiquer que les populations pourraient supporter la mortalité apparente par la pêche européenne à la senne estimée dans cette thèse. Cela semble donc confirmer le faible impact de la pêcherie sur ces populations, même s'il faut garder à l'esprit que celui-ci s'ajoute aux autres impacts, létaux ou non, subis par ces populations. Il faut cependant noter que sur certaines zones de pêche où les calées associées à la mégafaune sont moins fréquentes (i.e. sur la côte nord-est de l'Afrique dans l'hémisphère nord et en Mer d'Arabie), de très petites populations de baleines (notamment de baleine à bosse) pourraient être sensibles à des taux de mortalités par pêche de l'ordre de celles observées dans cette thèse (i.e. 3% pour les baleines). De la même manière, il convient de noter que des zones importantes pour la reproduction des requins baleines, telles que des zones de mise bas avec la présence de femelles gravides, sont surement localisées au milieu de l'Atlantique équatorial et proche de la Mauritanie. La

pêche à la senne dans ces régions, bien que capturant plus rarement des requins baleines par rapport à d'autres régions telles que la zone côtière du Gabon à l'Angola, pourrait également potentiellement impacter les populations de requins baleines. L'identification de zones clés pour la reproduction des requins baleines et des cétacés, ainsi que des régions supportant de très petites populations de cétacés est donc un enjeu important, et celles-ci pourraient être étudiées avant la formulation de mesures de conservation vis-à-vis de ces espèces de la mégafaune.

En complément de ce travail de thèse sur les espèces encerclées, d'autres espèces de la mégafaune, principalement capturées en tant que prises accessoires et remontées à bord des senneurs, peuvent également être impactées par la pêche thonière à la senne dans les deux océans. Par exemple, le requin soyeux, première espèce de chondrichthyen Amandè *et al.* 2011) a également été identifiée comme la prise accessoire la plus abondante sous baleines et requins baleines, et est considérée Hutchinson *et al.* 2015 Rice and Harley 2013). D'autres espèces de requins, tels que le requin océanique, dans l'océan Indien, et les requins marteaux dans l'océan Atlantique, sont également relativement abondantes en tant que captures accessoires dans les quatre modes de pêche. Cependant alors que les premiers ont Tolotti *et al.* 2015b), il y a un manque général d'information sur les requins marteaux et leur capture par la pêche à la senne dans l'est de l'océan atlantique et l'ouest de l'océan Indien. Les tortues marines sont également accidentellement capturées sous tous les modes de pêches, avec une variabilité Bourjea *et al.* 2014). Enfin, les raies manta, plutôt capturées sous bancs libres, notamment dans l'océan Atlantique, sont également retrouvées sous baleines et requins baleines, mais ont été généralement peu étudiées dans Croll *et al.* 2015). Il faut noter que des strates spatio-temporelles identifiées comme ayant de forts taux de captures ou d'interactions sont partagées par plusieurs de ces espèces et celles étudiées lors de cette thèse, dans les deux océans. Celles-ci pourraient donc être utilisées pour la mise en place de mesures spatio-temporelles de réduction des prises accidentelles. En parallèle, des méthodes de « bonnes pratiques » de libération d'individus Poisson *et al.* 2014b) ont été développées et doivent continuer à être encourager pour diminuer l'impact de la pêche à la senne sur les prises accessoires et les encerclements d'espèces vulnérables de la mégafaune. De plus, des mesures d'atténuation de l'impact de la pêcherie sur les prises accessoires sont en développement, notamment vis-à-vis des requins soyeux. Il faut également souligner que l'impact apparent de la pêche à la senne sur toutes ces espèces de la mégafaune pourra, dès à présent, être relativement bien quantifié grâce à une couverture d'observateurs scientifiques

de 100% dans l'océan Atlantique et ∼40% dans l'océan Indien.

Au niveau mondial, deux autres zones géographiques sont également très importantes pour la pêche thonière à la senne: l'est et l'ouest de l'océan Pacifique. Nous avons donc comparé les résultats de cette thèse avec les connaissances sur les interactions pêche thonière à la senne/ mégafaune dans ces océans. Au niveau de l'océan Pacifique est, les principales interactions se font avec les dauphins, comme en témoigne le nombre de calées réalisé sur ce mode de pêche qui est majoritaire dans cet océan. Les mortalités de dauphins ont été très réduites avec moins de 2000 individus par an, en comparaison avec plusieurs centaines de milliers dans les années 1960s et 1970s, grâce à l'adoption de modifications technologiques de la senne et du changement dans la méthode de pêche sur dauphins. A l'opposé, les calées associées aux baleines et aux requins baleines semblent très peu fréquentes, mais peu d'études ont spécifiquement étudié ces modes de pêche. Dans l'océan Pacifique ouest par contre, les taux de calées associées aux requins baleines (0,7–1,5%) et aux baleines (1,6–2,5%) sont similaires, bien que légèrement plus faibles, à ceux estimés dans cette thèse pour les océans Atlantique et Indien. Les taux de mortalités sont quant à eux plus élevés dans le Pacifique ouest (7–14% pour les requins baleines et 6% pour les baleines). Par ailleurs dans l'océan Pacifique ouest, la distribution de ces deux modes de pêche dans la zone de pêche principale (20°S–20°N) ne semble pas varier selon les saisons. Par contre, l'expansion de l'effort dans la partie nord de l'océan (au dessus de 20°N), suite à des mesures de régulation de la pêche sous DCP, pourrait conduire à un report de l'effort de pêche sur les requins baleines, où les calées associées à ces animaux étaient historiquement plus fortes qu'au niveau de la zone tropicale. Des études utilisant des simulations de Monte Carlo pourraient donc être envisagées pour évaluer un potentiel report de l'effort de pêche sur requins baleines dans cette zone située au nord de l'océan Pacific ouest.

Dans le futur, il apparait donc important d'étudier plus en détails les interactions entre la mégafaune et la pêche thonière à la senne dans l'océan Pacifique (est et ouest), par exemple en utilisant des méthodes similaires à celles utilisées dans cette thèse. Dans cette optique, une comparaison à l'échelle de l'océan mondial serait très intéressante. De plus, dans le Pacifique ouest, de plus fort taux de mortalité ont été enregistrés, notamment pour les requins baleines, il est donc important d'étendre l'expérience de marquage à cet océan (actuellement en cours) et d'inciter les équipages à l'utilisation de la méthode de «bonne pratique» de libération pour les individus encerclés. Ces deux points sont d'ailleurs à rechercher afin d'estimer de façon correcte les taux de survie post-encerclement et d'étudier les déplacements des requins baleines y compris hors des zones de pêche à la senne afin de couvrir l'ensemble de leur habitat. Toujours dans l'optique de l'approche écosystémique de la gestion des pêcheries, il est indispensable d'étendre les connaissances aux les autres espèces

de la mégafaune capturées de manière accidentelle, notamment les raies manta et les requins marteaux, encore peu connues. Enfin, il est fondamental que les ORGPs prennent en compte les prises accessoires lors de la formulation de mesures de gestion des stocks de thons tropicaux, tant dans une approche d'exploitation équilibrée de l'écosystème épipélagique («balanced harvest») que pour protéger les espèces vulnérables. Actuellement des mesures visant à limiter le nombre de DCP déployés sont mises en place dans les océans Atlantique et Indien par les ORGP thonières relevant de ces océans. De simples simulations du comportement de navires de pêche, se basant sur des probabilités conditionnelles de présence telles que celles utilisées dans cette thèse, permettraient d'anticiper les conséquences potentielles d'une diminution du nombre de calées effectuées sur DCP par bateau, à la fois sur les captures de thons, les espèces accessoires et les calées associées à la mégafaune. Le résultat des simulations pourrait servir de base aux négociations entre états pêcheurs membres de ces commissions ou entre diverses flottilles.

L'analyse quantitative des interactions entre la pêche thonière à la senne et la mégafaune adoptée tout au long de cette thèse apporte des connaissances sur des espèces vulnérables et importantes pour le fonctionnement des écosystèmes marins, et contribue ainsi à la mise en place d'une AEP applicable à la pêche thonière tropicale.

Chapter 1

General introduction

1.1 Context

Various natural and anthropogenic threats impact marine megafauna species world- Baum *et al.* 2003 Wallace *et al.* 2011 Magera *et al.* 2013). This denomination for large marine vertebrates includes several taxonomic groups, such as mammals, chon- Lewison *et al.* 2004 Žydelis *et al.* 2009 Senko *et al.* 2014a). The threats that their populations have to face consist of target and non-target fishing or harvesting, habitat destruction, pollution, ship traffic, pathogens, climate change and Halpern *et al.* 2008 Hoffmann *et al.* 2010). Yet, in this array of threats from human activities, the major ones are considered to be targeted fisheries and Stevens *et al.* 2000 Lewison *et al.* 2004 Read *et al.* 2006 Wallace *et al.* 2011). This overall extensive and increasing human pressure has lead to the decline of many species, especially species with particular inherent biological characterics, such as late maturity, low fecundity and high longevity, limit marine Musick *et al.* 2000 Schipper *et al.* 2008 Žydelis *et al.* 2009).

The extent, major cause and period of the decline however vary between groups. For instance, large whale populations have been severely depleted by extensive whaling Freeman 2008). Commercial whaling was prohibited by the International Whaling Commission (IWC) in 1986 (www.iwc.int). The recovery of Freeman 2008), and sometimes limited by factors Cassoff *et al.* 2011 Magera *et al.* 2013 Thomas *et al.* 2016). Likewise, small cetaceans and pinnipeds have been highly captured, but mainly as bycatch of several fishing gears (e.g. mainly gillnets, as well as trawl, longlines, Read *et al.* 2006 Kiszka *et al.* 2008 Moazzam and Nawaz 2014). This has led to the sharp decrease of many populations, with small Freeman 2008 Magera *et al.* 2013). Concerning shark species, bycatch rates are also very high for some fisheries Francis *et al.* 2001 Clarke *et al.* 2006 Carlson *et al.* 2012 Bezerra *et al.* in press). In addition, the increasing demand since 1990s of high valued shark fins has also led to the development of targeted fisheries and concerns have been raised for several Stevens *et al.* 2000 Clarke *et al.* 2007 Dulvy *et al.* 2008). Similarly, Dulvy *et al.* 2008 Ward-Paige *et al.* 2013 Croll *et al.* 2015). While the decline of some shark and ray populations have been documented, high bycatch rates, illegal fishing (i.e. shark-finning) as well as non-apparent entanglements in fishing gear (i.e. "ghost fishing") make difficult

Stevens *et al.* 2000 Musick *et al.* 2000 Filmalter *et al.* 2013). Finally threats to turtle populations vary across regions but include mostly fishery bycatch (longlines, gillnets, trawls and ghost fishing), harvest (utilization of eggs, shell or Lewison *et al.* 2004 Wallace *et al.* 2011), with Wallace *et al.* 2013).

Recognizing these population declines and the need for conservation actions, the non- IUCN 2015,www.redlist.org) has listed most marine megafauna species from "Near Threatened" to "Critically Endangered". Some species are also included in Appendix I or II of The Convention on International Trade in Endangered Species of wild fauna and flora (CITES, www.cites.org), as well as in Appendix II of the Convention of Migratory Species of Wild Animals (CMS; www.cms.int). Over the last decades, this general awareness toward marine megafauna vulnerability evolved with growing public interest for these species. All over the world, eco-tourism and diving industry have been developed for tourists to get close to these large animals: e.g. whale watching, snorkeling with whale sharks or diving with marine turtles, sharks or rays. Many countries have therefore realized that these species were worth protecting, as their values could be higher alive in their natural environment than captured Hoyt and Hvenegaard 2002 Cisneros-Montemayor *et al.* 2010).

Conservation measures have however mostly grown in coastal areas. While the anthropogenic pressure is very high in these ecosystems, marine megafauna species are often also relatively well studied. One of the main conservation measures for all marine species and ecosystems, since a few decades has been the establishment of Marine Protected Russ and Alcala 2004 Speed *et al.* 2010 Senko *et al.* 2014b). However marine megafauna species are often wide ranging species that undertake long migrations. The benefits of MPA and local management plans for these species may therefore be less obvious Russ and Alcala 2004 Chapman *et al.* 2005). Indeed the effectiveness of MPA highly depends on the species considered spending a large portion of their lives within the MPA Kramer and Chapman 1999 Graham *et al.* 2012). This would therefore likely not be the case Eckert 2006 Olsen *et al.* 2009 Hueter *et al.* 2013). In this way, they may also experience cumulative Game *et al.* 2009). In addition, the fact that they will spend some time in oceanic ecosystem may complicate even more their management and conservation. Indeed, in the open-ocean, distances from land make species more difficult to study and monitor, and the anthropogenic impacts may also be Dulvy *et al.* 2008). In addition, while states are responsible for the management of their marine resources within their Economic Exclusive Zone (EEZ, 200 nautical miles;

UNCLOS 1982), most of the oceanic ecosystems are within international waters (~ Sumaila *et al.* 2007). Therefore, due to the complexity of dealing with several countries that may have various and divergent interests, high seas monitoring is more complicated Dulvy *et al.* 2008 Game *et al.* 2009). In addition, implementing conservation measures in the high seas often takes time and may remain ineffective. To overcome these challenges, the identification of key areas (i.e. mating or calving grounds, nursery areas, feeding frontal areas) may be seen as a conservation priority Notarbartolo-di Sciara *et al.* 2008). Similarly, the identification of main bycatch areas, as well as the development of bycatch mitigation measures may be seen as equally important Žydelis *et al.* 2009 Senko *et al.* 2014b Lewison *et al.* 2014). Finally, recently NGOs and some scientist have also proposed the implementation of large Game *et al.* 2009 Kaplan *et al.* 2013 White and Costello 2014).

The preoccupation toward fishery impact on marine megafauna and other species Read *et al.* 2006 Dulvy *et al.* 2008 Wallace *et al.* 2013 Lewison *et al.* 2014). This went along with the Pikitch *et al.* 2004) or Ecosystem Approach to Fisheries (EAF), which was the term adopted by the Reykjavik FAO FAO 2003). Such approach was initiated by the FAO Code of Conduct for Responsible Fisheries in 1995, which provided a complete and operational Garcia *et al.* 2003). This code of conduct calls for integrated management, respect of the ecosystem, account of the environment, biodiversity and species interdependence. In addition it recommends the application of a Garcia *et al.* 2003). It was then complemented by the EAF, which recognizes the interdependence between human well-being and ecosystem health, as well as the necessity to maintain ecosystem productivity for present Ward *et al.* 2002). Therefore this approach take into account biotic, abiotic and human components of ecosystems and their interactions when planning fisheries FAO 2003). Similarly, the Convention on Biological Diversity adopted in 1992 CDB 1992) calls for conservation of species, genetic and ecosystems, in order to maintain ecosystems structure and functioning. In this way, European Union (EU) has also developed the "Marine Strategy Framework Directive" to effectively protect the marine environment and diversity (EU 2008). This directive aims to reach a "Good Environmental Status" (GES) of EU waters by 2020, meaning that they provide "ecologically diverse and dynamic oceans and seas, which are clean, healthy and productive" and that "the use of marine environment is sustainable so it can be maintained for current and future generations". Several indicators

of GES have therefore been identified, including maintenance of biological diversity, marine food webs and exploited fishes stocks within safe biological limits.

1.2 The tropical tuna purse-seine fishery worldwide

1.2.1 Short history of the fishery and the institution of Regional Fishery Management Organizations

In the pelagic ecosystem, the main targeted species caught by industrial longliners, Juan-Jordá *et al.* 2011). Catches of these species have globally increased in the last decades until reaching a FAO 2014). This corresponds to 9% of the total marine fishery production. The three major tropical tuna species, skipjack *Katsuwonus pelamis*, yellowfin *Thunnus albacares* and bigeye *Thunnus obesus* 1.1) are the most productive species, representing 58, 27 and 8% of the total catch (from all type of gear), respectively. The first one, the skipjack tuna, is smaller (maximum length of 108 cm Collette and Nauen 1983) than the two other species, with a size at maturity (L_{50}; fork Cayré and Farrugio 1986 Hazin *et al.* 2001 Grande *et al.* 2014) and is a relatively fast growing and fecund species. On the other hand, yellowfin and bigeye Reiner 1996 IGFA 2001) have higher length Albaret 1977 Matsumoto and Miyabe 2002 Zudaire *et al.* 2013 Cayré *et al.* 1988).They are therefore considered to be more Juan-Jordá *et al.* 2015b).

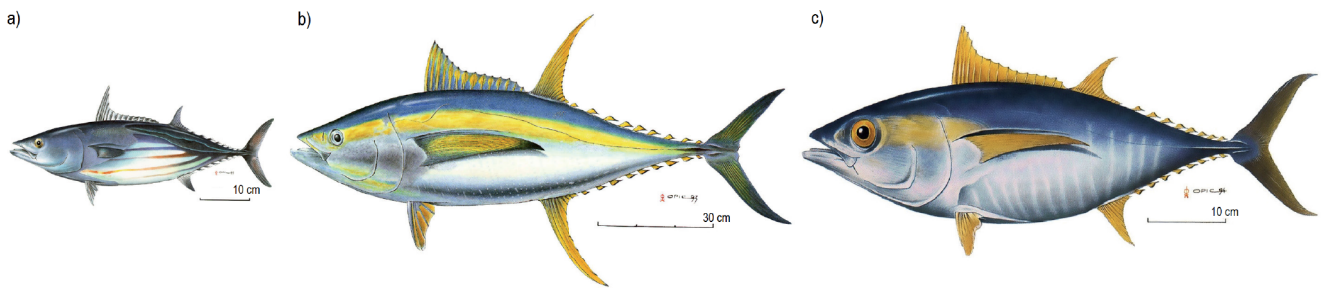

Figure 1.1 The three main species of tropical tuna: a) skipjack *Katsuwonus pelamis*, b) yellowfin *Thunnus albacares* and c) bigeye *Thunnus obesus* tunas (copyright P. Opic).

After the original developments of longline and baitboat (pole-and-line) fisheries in the 1950s, the purse-seine fishery is now the major gear catching tropical tunas worldwide Miyake *et al.* 2004). This fishery developed in the 1960s in the eastern Pacific Ocean (EPO) and eastern Atlantic Ocean (EAO), when US (EPO) and French and Spanish (EAO)

purse-seiners progressively replaced baitboats. After that, in the 1980s a large proportion of the Atlantic French and Spanish purse-seiners moved to the western Indian Ocean (WIO), starting a new productive fishery. During the same period, the Pacific purse-seine fishery Miyake *et al.* 2004) and a Gaertner and Medina-Gaertner 1999). From that time on, additional countries have joined the industrial tuna purse-seine fishery worldwide (e.g. Japan, Brazil, Mexico, Venezuela, Ghana, Seychelles), and these four ocean basins are still the main tropical tuna fishing grounds nowadays.

Tuna Regional Fishery Management Organizations (tRFMO) have been established 1.2). These intergovernmental organizations carry out data collection and scientific monitoring of all tuna and tuna-like (i.e. billfishes) fisheries within the areas covered by each commission. The tRFMOs managing, among other species, tropical tunas are the Inter-American Tropical Tuna Commission (IATTC), the International Commission for the Conservation of Atlantic Tunas (ICCAT), the Indian Ocean Tuna Commission (IOTC) and the Western and Central Pacific Fisheries Commission (WCPFC), respectively established in 1949, 1966, 1993 and 1.2). Their primary objective is to ensure through effective management the long-term conservation and sustainable use, for food and other purposes, of tunas and tuna-like stocks. Nevertheless, the WCPFC, the most recent tRFMO, is the only commission not using the term "tuna and tuna-like species" but instead refers to "highly migratory fish stocks". This corresponds to the fish species included in the Annex I of the 1982 United Nations Convention on the Law of the Sea (UNCLOS), which in addition to scombrid species and billfishes also include dolphin fishes and oceanic sharks (e.g. *Carcharhinidae*, *Sphyrnidae*, *Alopiidae* or the whale shark *Rhincodon typus*). The tRFMOs are divided into a political component, composed by the decision-maker contracting parties and an advisory scientific component. Therefore decisions are taken, not only based on scientific recommendations, but also taking into account other aspects, such as economic and social concerns.

In addition, two tRFMOs have explicitly adopted an EAF, as well as the precautionary approach. The WCPFC, and the updated IATTC convention agreement (i.e. the Antigua Convention of 2008) make explicit reference to the 1995 UN Fish Stocks Agreement (UNFSA) stating the "commitment to responsible fisheries and the need to avoid adverse impacts on the marine environment, preserve biodiversity, maintain the integrity of marine ecosystems and minimize the risk of long-term or irreversible effects of fishing operations". On the other hand, the two other tRFMOs, ICCAT and IOTC have not formally adopted an EAF, but have assimilated some of the concepts generally accepted in the UNCLOS and the UNFSA

through the adoption of specific management measures. Nonetheless these two tRFMOs have a scientific committee devoted to EAF management. Indeed, with the aim of monitoring and mitigating the effects of tuna fisheries on the pelagic ecosystem, specific working groups have been created in each tRMFO (e.g. "Sub-Committee on Ecosystems", "Working Party on Ecosystems and Bycatch").

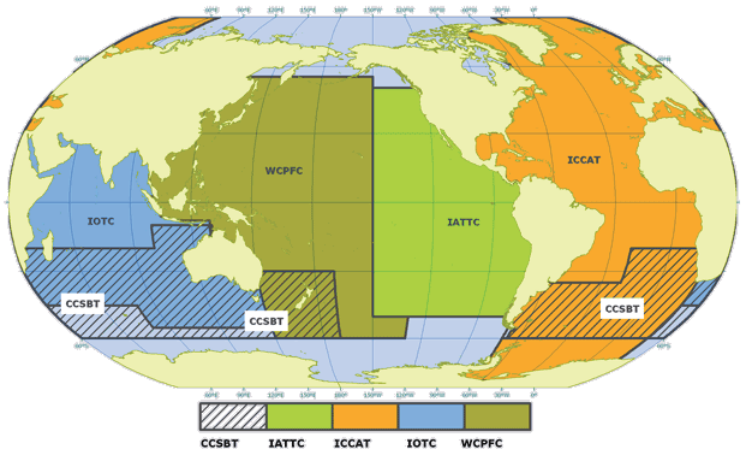

Figure 1.2 Tuna Regional Fishery management organizations (tRMFO): IATTC (Inter-American Tropical Tuna Commission), ICCAT (International Commission for the Conservation of Atlantic Tunas), IOTC (Indian Ocean Tuna Commission), WCPFC (Western and Central Pacific Fisheries Commission) FAO 2012).

Overall, it can be considered that the principle of EAF management is generally accepted Juan-Jordá *et al.* 2015a). However the formal development of an operational EAF management plan has not been achieved by any of the tRFMO. The focus of the management plans remains avoiding that the targeted tuna and tuna-like species spawning-stock biomass (SSB) fall below a level impacting recruitment. Some effort has however been made on reducing and/or mitigating the impact of the fisheries on some bycatch species (i.e. sharks, rays, turtles, seabirds, and marine mammals). Nevertheless the lack of consideration for inter-specific interactions, especially trophic, and for habitats prevents the recognition of an EAF management. In addition, tRMFOs also face the main limits of EAF implementation. These involve the difficulties of connecting the different components of an ecosystem and defining ecosystems reference points, as well as the perception that such approach would be Tallis *et al.* 2010). Therefore, the main regulation implemented by tRFMOs generally focus on limiting overexploitation of targeted stocks. In the last decades, the most common management tool have been catch Harley and Suter 2007 Torres-Irineo *et al.* 2011 Kaplan *et al.* 2014 Torres-Irineo *et al.* 2016). However, generally there has been little, if any, consideration of the ecological impact that these restrictions may cause, especially for

non-targeted species.

1.2.2 The tuna purse-seine's fishing modes

The tRMFOs manage tuna fisheries within their jurisdiction area. Each fishery will however affect differently targeted species, ecosystems and bycatch. For instance the longline Dagorn *et al.* 2013). In addition, for the latter, these impacts will also vary with the fishing mode (i.e. determined based on the visual cues at the surface of the seas that could indicate the presence of tuna schools).

Firstly, one fishing mode consists in encircling free-swimming tuna schools ("**free school set**"). This has been performed since the development of the fishery in all oceans. Tuna schools are located by the presence of flocks of birds or the deformation of the water 1.3). The detection of these cues is made using binoculars and bird radars. This latter technology has been implemented in the late 1980s and has highly increased the efficiency of free Hervé *et al.* 1991). Once located, purse-seiners will encircle tuna schools with the seine, then stop the engine in order to purse the seine for about 20 minutes before 1.4 for the different steps of a purse-seine fishing set). During this process the tuna school may escape by diving or by going under the purse-seiner through a net-free area. Hence, the success of this fishing mode depends on skippers' ability and experience and requires extensive searching time. The typical tuna catch in free school consists, of monospecific school of large adult yellowfin tuna (>30 kg or >100 cm FL). However catches of monospecific free schools of skipjack tuna have been very common in Fonteneau *et al.* 2000a). Finally the bycatch rate for free Amandè *et al.* 2010 2012), and the species incidentally captured include bony fishes (e.g. *Coryphaenidae*, *Scombridae*), billfishes (i.e. *Istiophorus spp.*), sharks (e.g. silky shark *Carcharhinus falciformis*), rays (*Mobulidae* Torres-Irineo *et al.* 2014 Lezama-Ochoa *et al.* 2015).

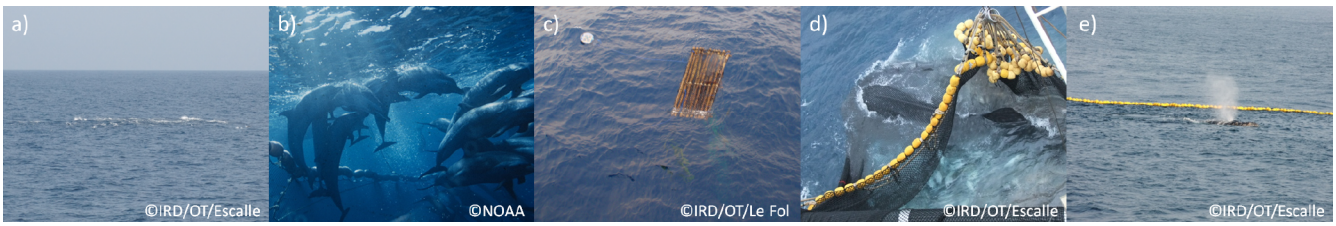

Figure 1.3 The tropical tuna purse-seine fishing modes: a) free school's cue, b) dolphin set, c) Fish Aggregating Device, d) whale shark associated set, and e) whale associated set.

A second fishing mode consists in capturing tuna schools associated with dolphin herds ("**dolphin set**") and occurs only in the EPO. The tuna-dolphin association is composed of large yellowfin tunas (>10kg) and pantropical spotted dolphin *Stenella attenuata*, spinner dolphin *Stenella longirostris*, common dolphin *Delphinus delphis* or less frequently striped dolphin *Stenella coeruleoalba* 1.5). This association has been considered to increase prey localization and foraging efficiency, as well as possibly increase chances for tuna of Stuntz 1981 Fréon and Dagorn 2000). The tuna dolphin association is promoted in the EPO by a shallow thermocline, warm sea surface temperature and a thick oxygen minimum zone, which Edwards 1992 Scott *et al.* 2012). The tuna-dolphin Anderson 2014 Levenez *et al.* 1979 Stuntz 1981 Potier and Marsac 1984 Stretta and Slepoukha 1986). In the EPO, dolphin sets occur as follows. First, when skippers detect a group of dolphins and confirm the presence of associated tunas, they launch speedboats to chase them (20–30 minutes). Then when the dolphin herd has slowed down, the whole tuna-dolphin group is encircled. This has therefore historically led to high dolphin mortality in the process. In the 1960s and early 1970s the dolphin mortality was estimated at over hundreds of thousands of animals Hall 1998), mostly made by US purse-seiners. Following general awareness of the issue and great controversy regarding its ecological, legal, economic and political aspects Joseph 1994 Scott 1996), the US Marine Mammal Protection Act was instituted in 1972 in America. This law set a general limit for dolphin mortality generated by US vessels (78 000 then 20 500 per year) and also created a mandatory scientific observer program Joseph 1994). In the mean time, many Latin American Countries had joined the EPO purse-seine fishing fleet, which led to the tuna-dolphin problem becoming international. In addition, partly due to the dolphin legislation, but also because of limited access to Latin America coastal fishing zones and the decrease of yellowfin abundance, many US vessels migrated to the WCPO (106 vessels in the EPO in 1976, and 38 in 1984). Finally in 1990, the US Congress instituted the "dolphin safe" label for tuna fished without dolphin mortality. While many US vessels considered that it was not economically viable to stay in the EPO (7 Joseph 1994), Latin American countries were still fishing on dolphins in the EPO. Yet the annual dolphin mortality kept decreasing, due to technological developments and gear modification, such as i) the "backdown" procedure, consisting in the vessel going in reverse right after encircling the tuna-dolphin group in order to sink the corkline and allowing dolphins' escape, ii) the "Medina panel", consisting of a smaller-meshed net in an area where dolphin usually get entangled, and iii) the use of

Hall 1998). In 1996, 88% of the dolphin sets had zero dolphin mortality, and the average mortality per set was of 0.33 individual. Nowadays the number of dolphin set still represent half the sets completed in the EPO (45% IATTC 2010).

The associated catch is constituted of large yellowfin tuna with very few bycatch (sometimes sharks, billfishes, *Coryphaenidae* Hall 1998).

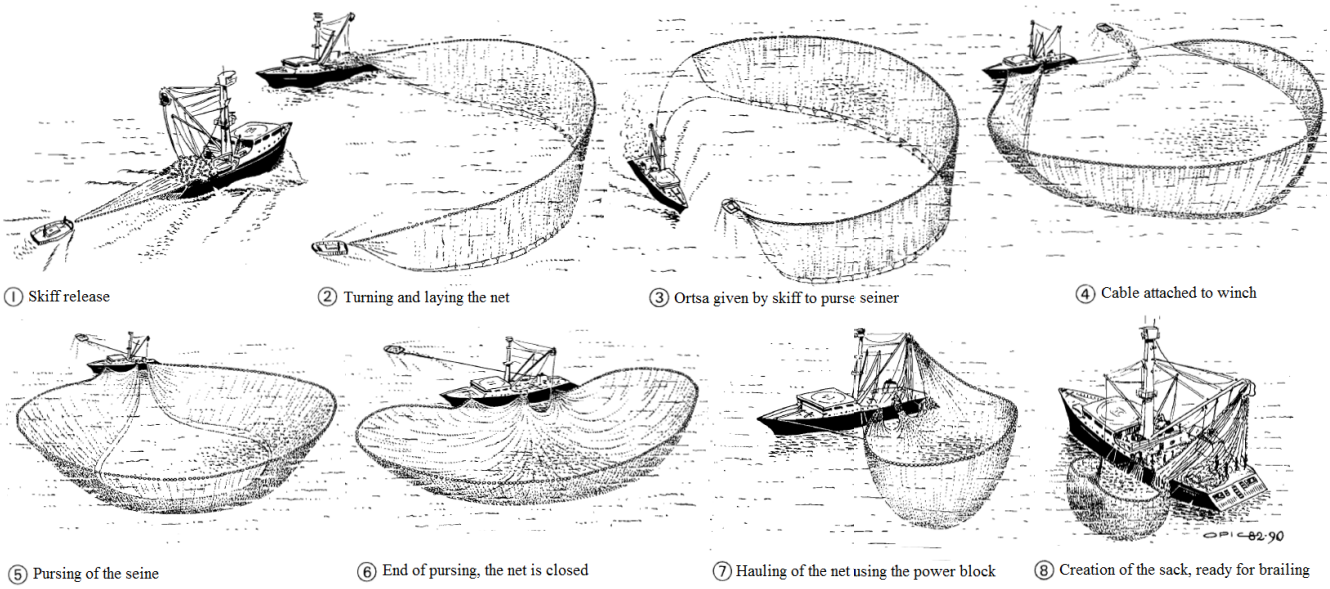

Figure 1.4 The different steps of a tuna purse-seine set. © IRD, Stequert B., and Marsac F., 1992. Pêche thonière à la seine : évolution de la technique et bilan de dix années d'exploitation dans l'océan Indien, Figure 14. Editions de l'ORSTOM, Paris.

A third main fishing mode worldwide consists in setting on tuna schools associated with natural or artificial floating objects (FOB), or man-made Fish Aggregating Devices ("**FAD set**"). Tunas and other marine species are known to aggregate under natural floating objects (e.g. tree trunks, branches, kelp, vegetal debris, floating objects, or carcasses of sperm whale *Physeter macrocephalus*), as well as human residue (e.g. destroyed fishing gear, boards, cans). Two major and most credible hypotheses have been formulated to explain this aggregative behavior. First, the "indicator-FOB" hypothesis, which considers that FOB may act as indicators of productive areas. Indeed, most natural FOB originate and remain in rich terrigenous areas (i.e. river mouths, mangrove swamps), as well as often Hall 1992). Both areas are known to support highly productive environments. Second, as mentioned for the dolphin-tuna association, the "meeting point" hypothesis, which considers that isolated individuals or small-sized schools of a given species will have higher encounter rates with other schools Fréon and Dagorn 2000). This hypothesis also agrees with the same

evolutionary advantages as the schooling behavior: lower risk of predation, faster location Fréon and Dagorn 2000). For many years fishers have exploited this aggregative behavior as fishes are easier to detect and to capture. In the industrial purse-seine fishery, it started to be exploited in the 1960s, especially in coastal Fonteneau *et al.* 2000b). It has however been followed by the deployment of man-made FAD directly constructed with the aim of aggregating tuna schools and increase fishing efficiency. In the rest of the thesis, "FAD" will regroup both natural and artificial FOB and man-made FAD. They started to be highly deployed and Ariz and Gaertner 1999 Hall *et al.* 1999 Hallier and Parajua 1999 Hampton and Bailey 1999 Fonteneau *et al.* 2000b). The efficiency of FAD fishing was accelerated by the arrival of new technological developments to track FADs, such as radio beacons (late 1980s) and GPS Gaertner and Pallares 2002). This was also enhanced by the introduction of satellite echo-sounder buoys in the 2000s, which allow Lopez *et al.* 2014). The global catches on FAD have fluctuated worldwide with a general increasing trend in the EAO and WIO, up to 75% and 80% of the total yearly catch. In the WCPO and EPO, inter-annual variation were higher, with a maximum of 75 and 50% of the total catch recorded in the Fonteneau *et al.* 2013). Contrary to the two first fishing modes, FAD sets mainly catch small tunas of the three major tropical species, with an average size of 50 cm. This corresponds to adult skipjack, but juvenile yellowfin and bigeye tunas. Some ecological concerns have therefore rapidly been formulated on the sustainability of these two Gaertner and Medina-Gaertner 1999 Hall *et al.* 1999 Hallier and Parajua 1999 Hampton and Bailey 1999 Marsac *et al.* 2000 Hallier and Gaertner 2008), suggesting the potential displacement of tuna into suboptimal areas and leading to reduced food availability and decreasing body condition Hallier and Gaertner 2008 Fonteneau *et al.* 2013). In addition to these concerns regarding the targeted resource, FAD sets also generate a much higher bycatch than the other fishing Kelleher 2005). The species caught include other bony fishes (*balistidae*, *carangidae*, *coryphaenidae*, *scombridae*), billfishes (*makaira spp.*), sharks (mainly silky shark and whitetip shark *Carcharhinus longimanus* Hall 1998 Amandè *et al.* 2010 2012). In general, it is estimated that the bycatch on FAD sets represent 5–10% (including discard Fonteneau *et al.* 2013).

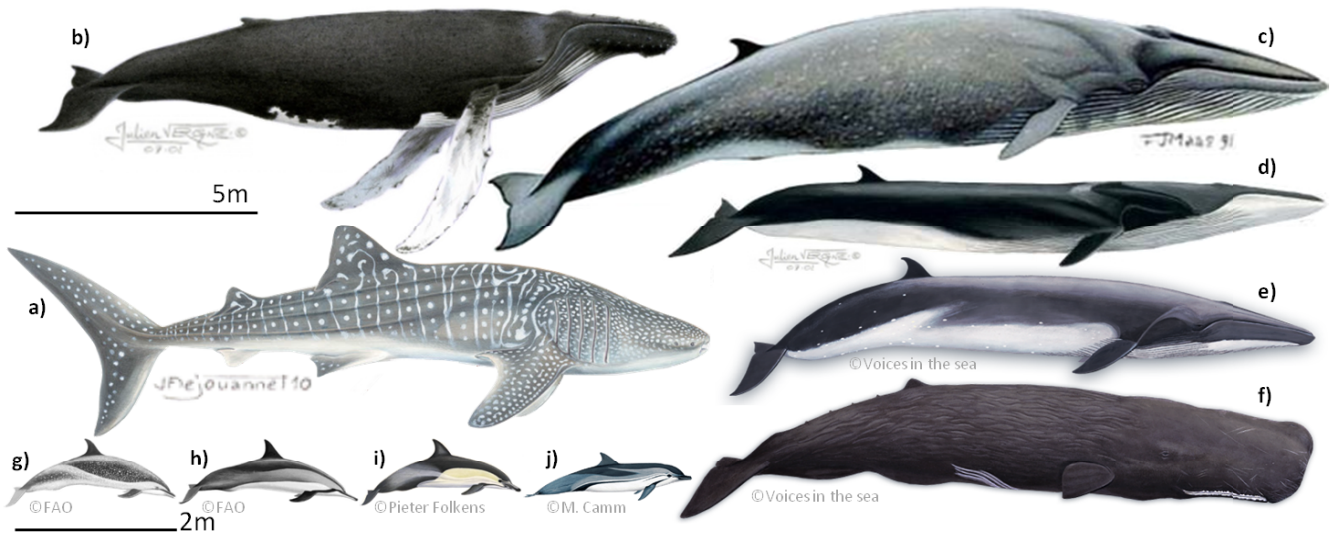

Figure 1.5 Megafauna species interacting with the purse-seine fishery worldwide: a) whale shark *Rhincodon typus*; baleen whales: b) humpback whale *Megaptera novaeangliae*, c) fin whale *Balaenoptera physalus*, d) sei whale *Balaenoptera borealis*, and e) Bryde's whale *Balenoptera edeni* ; f) sperm whale *Physeter macrocephalus*; and dolphin species: g) pantropical spotted dolphin *Stenella attenuata*, h) spinner dolphin *Stenella longirostris*, i) common dolphin *Delphinus delphis* and j) striped dolphin *Stenella coeruleoalba*. The scale is different between large animals (whale shark, baleen whales, sperm whale) and dolphins.

Fourthly, sets are also made on tuna schools associated with whale sharks ("**whale shark associated set** 1.5). This fishing mode is considered to be a specific type of FAD set where the whale shark acts as a "living FAD". Whale sharks typically swim slowly in sub-surface, which can, as any other inanimate floating object, aggregate several marine species. In this way and because of the similarity in their tuna catch species and size compositions, whale shark associated sets are commonly combined with FAD sets for Pallarés and Petit 1998). However whale sharks and tuna Hampton and Bailey 1999). In the southern Caribbean Sea, this fishing mode was the second most frequent Gaertner and Medina-Gaertner 1999). It also occurs in other oceans, but to a lesser extent. For instance, it has been documented in the EAO Stretta and Slepoukha 1986 Ariz and Gaertner 1999), where its represented 8% of the Hampton and Bailey 1999 Matsunaga *et al.* 2003 WCPFC 2010 Hall *et al.* 1999 Romanov 2002). Few studies have however precisely documented the tuna catch and bycatch on Stretta and Slepoukha 1986) found that most sets captured a

Medina-Gaertner and Gaertner 1991) found that most whale shark associated sets captured pure schools of yellowfin tuna (mostly >10kg, but also smaller ones), but the same authors

also found, a few years later, a higher proportion of skipjack in the sampling at landing sites Gaertner and Medina-Gaertner 1999 Pallarés and Petit 1998) agree with this second result, as they found similar species and size composition (i.e. skipjack tuna and juvenile yellowfin and bigeye tuna) between whale shark associated and FAD sets.

Finally, sets are also made on tuna schools associated with baleen whales (*Balaenopteridae*) ("**whale associated set**"). Worldwide the species recorded to associate with tuna schools are fin whale *Balaenoptera physalus*, sei whale *Balaenoptera borealis*, Bryde's whale *Balenoptera edeni*, minke whale *Balaenoptera acutorostrata* and humpback whale *Megaptera novaeangliae* 1.5). The tuna-baleen whale association has also been considered to be a feeding association. In the WCPO, tunas and baleen whales have been found in temporary aggregation to feed on balls of ocean anchovy *Stolephorus punctifer* Hampton and Bailey 1999). When fishers locate baleen whales, they will come near it to check the presence of tunas. Then the whole tuna school as well as the baleen whale will be encircled. Hampton and Bailey 1999 Romanov 2002) mentioned that fishers will tend to keep the whale inside the net as long as the pursing of the net continues, so the tuna do not escape with the whale. Once the set is pursed, the whale commonly escapes by punching a hole through the net. This fishing mode has been firstly recorded in the Caribbean, where the Gaertner and Medina-Gaertner 1999). However Stretta and Slepoukha 1986), the Hampton and Bailey 1999 Molony 2005 Hall *et al.* 1999) and in the Romanov 2002). As for whale shark associated sets, little information exists on the tuna catch and bycatch on whale associated sets. In the Caribbean Sea and the EAO, three Stretta and Slepoukha 1986 Medina-Gaertner and Gaertner 1991 Gaertner and Medina-Gaertner 1999 Pallarés and Petit 1998) found that species and size composition was similar between whale associated and free school sets (i.e. mostly large yellowfin tuna). Therefore, whale associated sets are commonly combined with free school sets for stock assessment objectives.

To sum up, the main tuna purse-seine fishing modes worldwide are FAD and free school sets, except for the EPO where dolphin sets is also one of the main fishing modes. Whale and whale shark associated sets, less frequent, are often combined with the two main ones for data management purposes. In addition, as highlighted in the previous paragraphs, while the tuna catch and bycatch captured in the main fishing modes are relatively well known, very little information exists on the species, especially non-targeted species, captured in association with whale shark and cetaceans. Such information is

important for management, but also gives an insight into pelagic inter-specific associations.

1.3 The European purse-seine fishery in the eastern Atlantic and western Indian Oceans

1.3.1 Environnmental conditions

The eastern Atlantic and western Indian Oceans are influenced by different environmental factors, which may also drive the spatio-temporal variability of species distribution and in turn the one of tuna fishery. It is therefore important to present the main oceanographic features of each ocean before dealing with the fishery.

Firstly, the EAO is mostly influenced by the Canary and Benguela Currents (Fig- 1.6). The Canary Current, goes southward along Morocco and Mauritania and generates a seasonal upwelling from Mauritania to Guinea Conakry between November and May Benazzouz *et al.* 2014). On the other hand, the Benguela Current, is going northward from South Africa to Gabon and also creating a seasonal upwelling between July and September Hardman-Mountford *et al.* 2003). Along the equator, the general flow runs westward toward Brazil (north and south Equatorial Currents). To the contrary, in the Gulf of Guinea, the north Equatorial Counter Current runs eastward above the equator from 20°W to the African Philander 2001). Two domes (Guinea and Angola), characterized by a shallower thermocline, can be identified when the Equatorial Counter Currents reach the African coast and turn toward the poles. Finally the Congo River, second largest river in the world, also highly influenced the Gulf of Guinea. Its river's discharge is the highest during the Marcello *et al.* 2011). This leads to the high input of fresh water as well as dissolved organic matter and natural FOBs in the oceanic ecosystem, Hardman-Mountford *et al.* 2003). It is noteworthy that several productive areas (upwellings, domes, river discharge) can be identified in this ocean, and may therefore potentially influence species distribution. In addition, the general strong current toward America will also influence drifting objects and animals. Finally, in this ocean, seasonal variability is relatively important, with seasons that could be defined as four quarters starting in January. On the other hand inter-annual variability appears relatively low compared to other oceans (e.g. Pacific Ocean highly influenced by "El Niño").

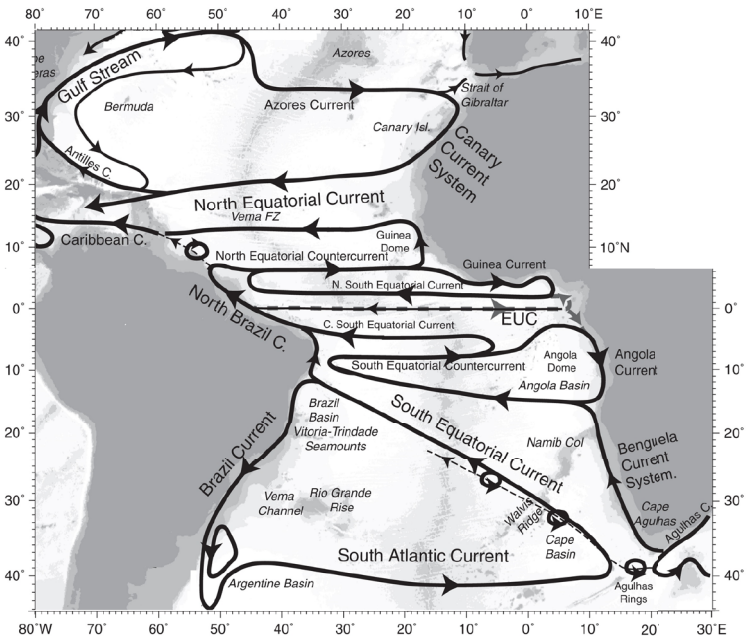

Figure 1.6 Schematic representation of the currents and bathymetry of the tropical and sub-tropical Talley *et al.* 2011).

Secondly, the WIO is highly influenced by monsoonal seasonality. This atmospheric phenomenon results from the geography of the ocean (surrounded by continents) and is characterized by the thermic flow reversing (asymmetry in the heat between land and sea). Therefore this also drives the reverse of the dominant winds between northern and southern hemispheres. In this way, two main monsoon periods can be identified: the north-east (NE) monsoon from December to March and the south-west monsoon (SW) from June to Schott *et al.* 2009). These are separated by two inter-monsoon periods: the intermediate south-west (ISW) monsoon in April–May and the intermediate north-east (INE) monsoon in October–November. During the NE monsoon the Somalia Current (southward) joins the East African Counter Current (EACC) (northward) under the Equator leading to the formation of the South Equatorial Counter Current (eastward). During this period an open ocean upwelling is also generated in the Seychelles-Chagos thermocline ridge (55°E–65°E; 5°S–12° Hermes and Reason 2008). In contrast, during the SW monsoon winds drag along the East African Counter Current until reaching the Somalia Current, which generates 1.7 Schott *et al.* 2009). Finally, all-year round the Mozambique Channel is characterized by the presence of productive mesoscale Schott *et al.* 2009 Tew-Kai and Marsac 2010). In this ocean higher inter-annual oscillation are detected due to the presence of a climatic phenomenon similar to "El Niño" in the Pacific Ocean, the "Indian Ocean dipole" occurring every 4–5 years. During the positive phase, Sea Surface Temperature (SST) and

rain are high off the African coast, but on the contrary, SST is abnormally low off Sumatra Saji *et al.* 1999). In addition, the thermocline deepens in the western part of the ocean, which has an influence on the purse-seine fishery as it increases the tuna schools habitat and Ménard *et al.* 2007). Similarly, the seasonal variability in productive environments (upwellings) will likely influence the species distribution.

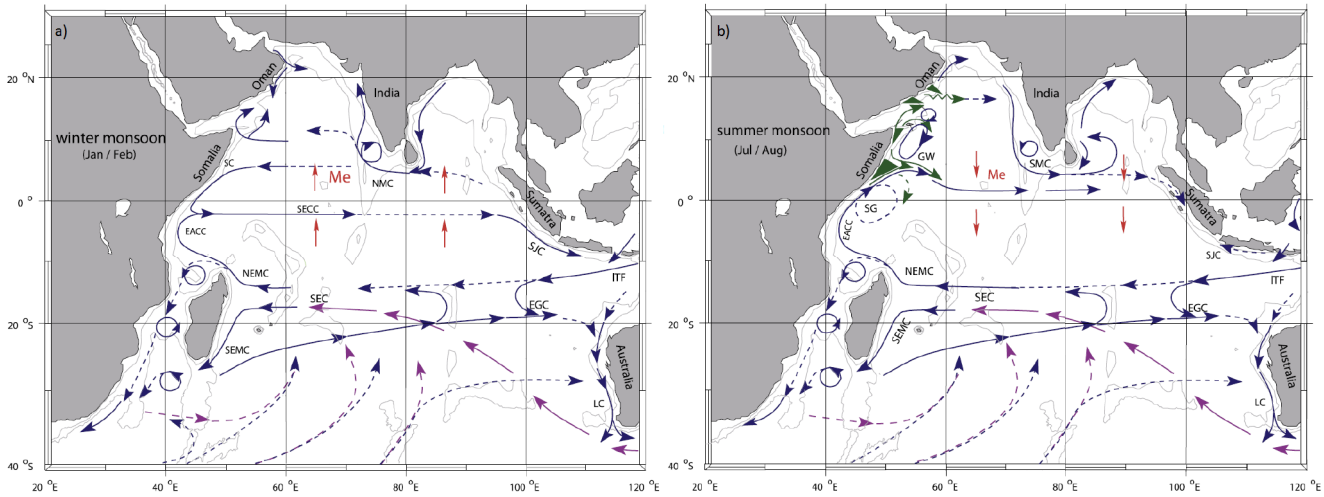

Figure 1.7 Schematic representation of the currents in the Indian Ocean during a) the NE monsoon Schott *et al.* 2009).

1.3.2 Distribution of purse-seiners' fishing effort and strategies

In the EAO and WIO, the two main purse-seine fleets are the French and Spanish (and associated flags). This European fleet captures on average 70% of the total yearly purse-seine tuna catch in both oceans. However, since the development of the fishery (since 2000s in the WIO), the number of operating vessels has generally decreased for both fleets Chassot *et al.* 2015b Delgado De Molina *et al.* 2015 Chassot *et al.* 2015a). Nevertheless this has been balanced by purse-seiners' increasing efficiency following the introduction of new technologies on board, such as bird radar, sonars, GPS and echo-sounder buoys on Lopez *et al.* 2014). This technological development has therefore come along with the general increase in the size of the purse-seiners. In the EAO, the number of purse-seiners has continuously decreased until reaching an annual average of 11 French and 31 Spanish operating vessels for the last ten years (23 in 1991 and 37). In addition to the increased efficiency, the inter-ocean migration of a large number of purse-seiners from the EAO to the WIO in the 1980s may also explain this decrease. This was caused by the decrease in Fonteneau 1991) and the fact that the fishery in Marsac *et al.* 2014). The overall number of fishing activities (i.e. fishing sets, searching activities and ship cruising between fishing areas)

1.8). In contrast, the number of fishing sets
1.8). The difference between
number of activities and number of fishing sets may be explained by i) the fact that less purse-seiners are present leading to less searching and cruising activities, but the increased efficiency maintained the number of sets, ii) the development of FAD fishing, which requires less searching time. In the WIO, the number of vessels highly increased at the beginning of
Chassot *et al.* 2015a), then decreased
to an annual average of 17 French and 25 Spanish operating vessels each year since 2005. The number of activities and fishing sets generally increased, especially in the 2000–2010
1.9).

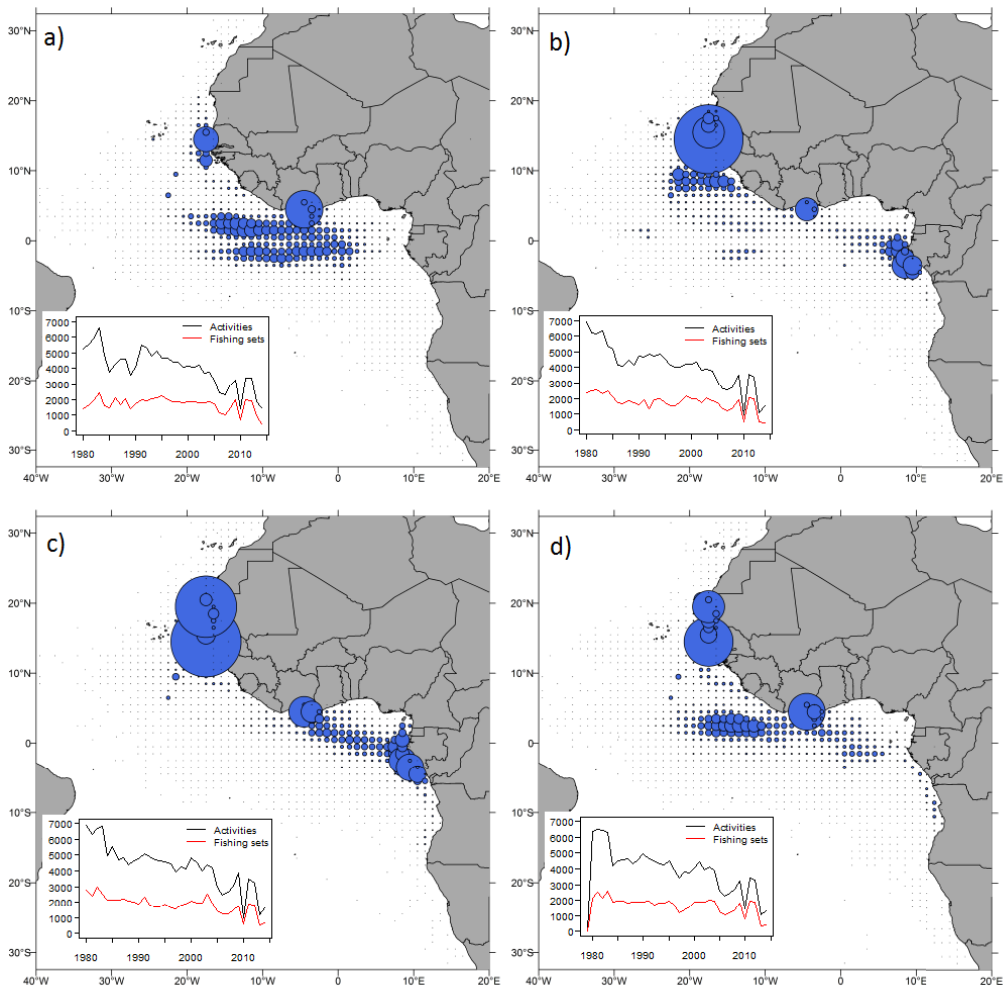

Figure 1.8 Spatial distribution in the number of European purse-seine fishing activities per season in the eastern Atlantic Ocean, and annual evolution of the number of activities and fishing sets per season for the 1980–2014 period. Panels a) to d) corresponds to seasons 1 to 4 (i.e. four quarters of months starting in January), based on European logbook data.

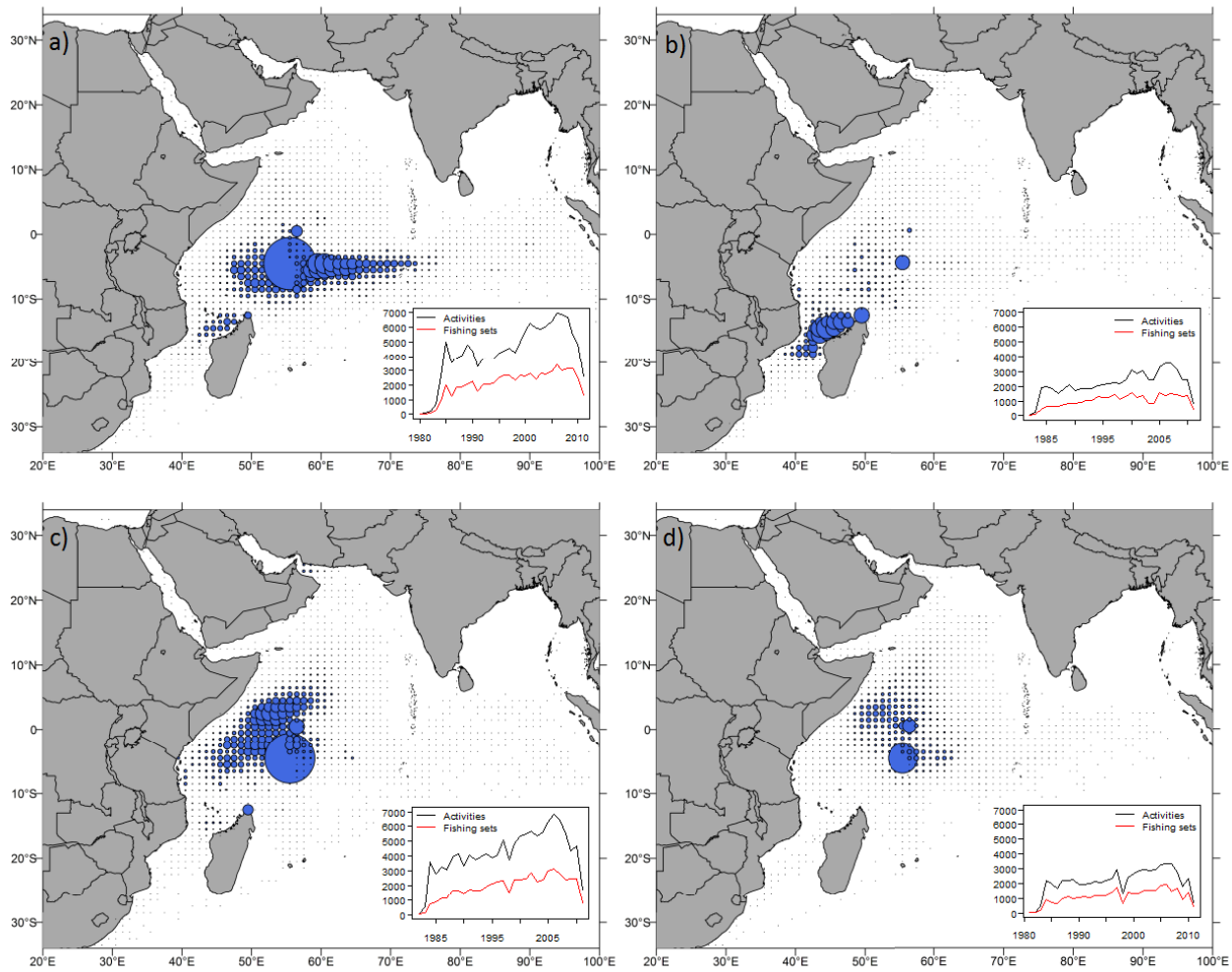

Figure 1.9 Spatial distribution in the number of European purse-seine fishing activities per season in the western Indian Ocean, and annual evolution of the number of activities and fishing sets per season for the 1980–2011 period. a) NE Monsson, b) ISW monsoon, c) SW monsoon and d) INE monsoon, based on European logbook data.

In both oceans, the distribution of fishing effort highly varies throughout the year 1.8 1.9). In the EAO, the effort is mostly concentrated i) in a central part of the Gulf of Guinea (5°S–5°N and 20°W–0°) during season 1, then ii) off Mauritania to Senegal and off Gabon during seasons 2 and 3, and finally iii) off Mauritania-Senegal and above the Equator from 20 to 10° 1.8). Therefore it can be noted that fishing in the Mauritania-Senegal region corresponds to the season of the upwelling, while in Gabon it is during the peak in the Congo's discharge. FAD fishing is widespread over all fishing grounds, but some areas have higher proportion of FAD sets. For instance the region off Gabon (high input of FOB), as well as a region above the equator from 20°W to 0° (i.e. FAD 1.10). In the WIO, a real cycle, following monsoonal seasonality, can be observed. The fishing effort is distributed in i) an area around the Seychelles from

45°E to 80°E mostly on free school set during NE monsoon (Seychelles-Chagos upwelling), ii) the Mozambique Channel on both FAD and free school sets during ISW monsoon, iii) an area north of the Mozambique Channel and off Somalia mostly on FAD set during SW monsoon (Somalia upwelling), and finally iv) an area off Somalia (FAD set) and around 1.9 1.10).

In addition to the general patterns observed, the French and Spanish fleets have different strategies, depending on the one chosen by the fishing companies of each country. After the expansion of FAD fishing in 1980s (WIO) and 1990s (EAO), Spanish companies have rapidly chosen to mostly target this fishing mode with large purse-seiners (>100m). As the capture associated with FAD sets is less risky in terms of null set and generally higher than on free school sets for successful sets, these large vessels became economically sound. This is further reinforced by the fact that they often are associated with supply vessels, which are not fishing but specifically dedicated to seeding, moving and visiting FADs. This has intensified over the last ten years with the development of echosounder satellite buoys (i.e. GPS buoys equipped with echosounder to estimate the abundance of tuna aggregated Lopez *et al.* 2014). The percentage of FAD sets performed by Spanish purse-seiners has therefore exceeded free school sets, and has now reached 80% of the 1.11). For the French fleet, the situation

Stretta and Slepoukha 1986) as well as after 2000. On the other hand, the number of sets 1.11).
The decrease in FAD sets in the late 1990s could be explained by the institution of a FAD Pianet *et al.* 2002). Over the last few years, the proportion of FAD sets increased again (∼40% of the sets nowadays). In the WIO, the dominance between FAD and free school has fluctuated, but French fishing is now dominated by FAD sets (60%). In addition, another factor has influenced the choice of a different strategy per fleet. Indeed Spanish crews are paid according to the tonnage captured (i.e. even if small tunas under FADs have lower price than large fish), while French crews are paid based on the value of the tuna catch (i.e. large tunas, captured on free school sets have higher commercial value).

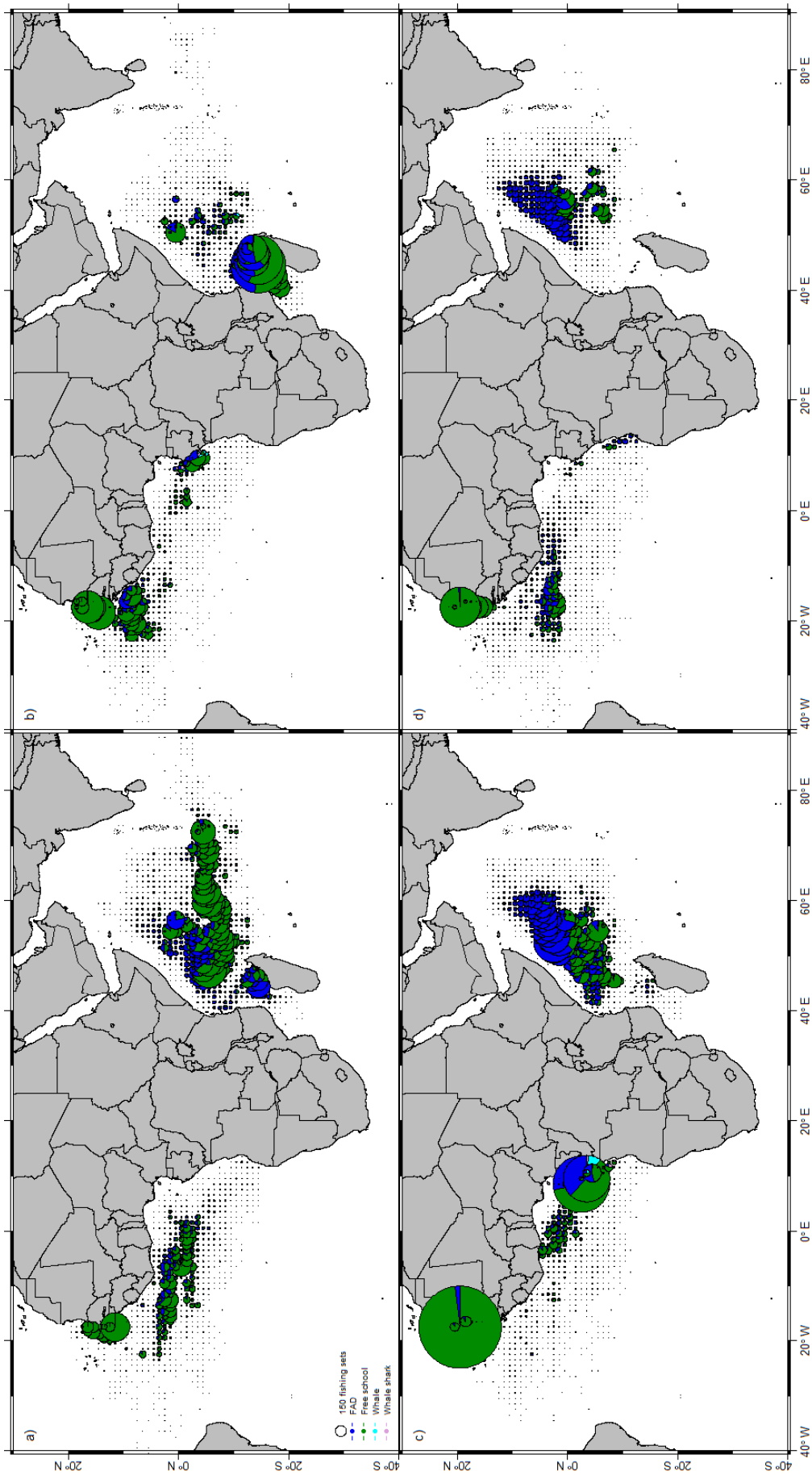

Figure 1.10 Seasonal distribution of the number of European purse-seine fishing sets per fishing mode for the 2005–2014 period in the Atlantic and Indian Oceans: a) season 1 and NE monsoon, b) season 2 and ISW monsoon, c) season 3 and SW monsoon, and d) season 4 and INE monsoon, based on European logbook data.

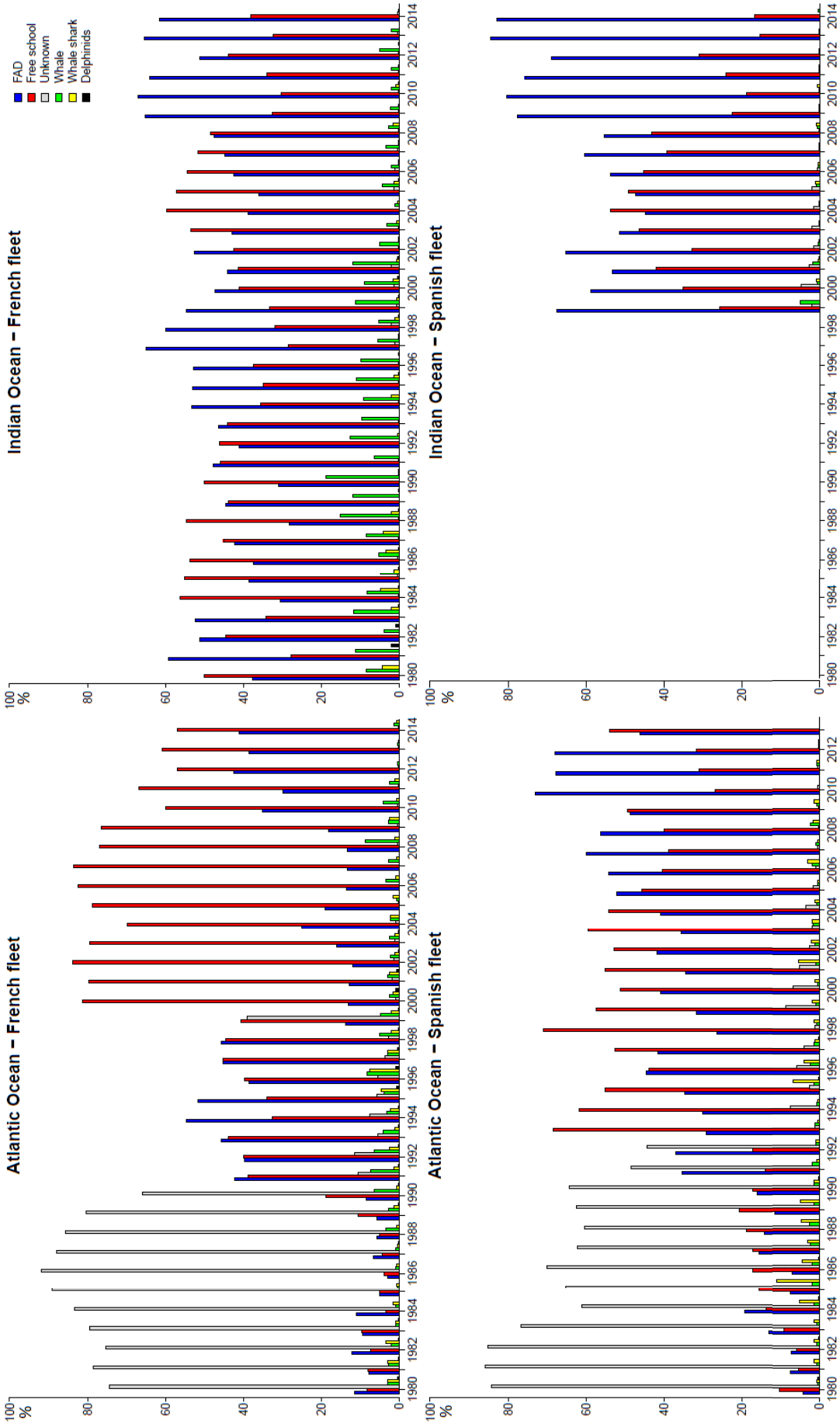

Figure 1.11 Annual variability in the proportion (%) of purse-seine fishing set per fishing mode in the Atlantic and Indian Ocean for the French and Spanish fleets for the 1980–2014 period. Before 1990, the fishing mode was often not recorded, however in the Atlantic Ocean, Stretta and Slepoukha 1986).

1.3.3 Megafauna associated fishing sets and information on the species involved

Both fishing fleets also target tuna schools associated with baleen whales and whale sharks. In the 1980s, these two fishing modes were considered to each represent ∼8% of the Stretta and Slepoukha 1986 Ariz and Gaertner 1999) and have also been recorded in the WIO but their importance for the fishery was not mentioned Romanov 2002 Levenez *et al.* 1979 Stretta and Slepoukha 1986 Potier and Marsac 1984 Coulmance 1995) but appeared to be very rare. Nowadays, whale and whale shark associated sets have also been 1.10), presumably due to the development of the more predictable FAD fishing, and little information exists on these sets in the EAO and WIO. In addition, in these oceans, due to the similarity in the tuna catches and for stock assessment purposes, whale associated sets are commonly combined with free school sets, and whale shark associated sets with FAD sets. Indeed, when the current sampling and data correction procedure (see next section) was established to estimate precise tuna catch composition by species and size category, it was found that the capture in whale associated sets was similar to free school set. Likewise the capture in whale shark associated set was found similar Pallarés and Petit 1998). However, no studies have specifically investigated the species captured, especially non-targeted, on the fishing modes. Globally, it is clear that there is a need for a quantitative study on the spatio-temporal distribution of these two megafauna associated fishing modes in the EAO and WIO.

Furthermore, no quantitative studies have estimated incidental catch and mortality induced by the purse-seine fishery on whale shark and cetaceans in these oceans. Currently, within a general framework of megafauna conservation, this is part of a key issue, that should be accounted for in an EAF management of tuna fisheries. In the case of encircled whale shark and cetaceans in the EAO and WIO, we will not refer to it as "bycatch", as considering 1.12). This will however not be the case for juvenile or small cetaceans (i.e. delphinids), which therefore could be considered as bycatch. Whale shark and cetacean encirclements could nevertheless be either intentional (when individuals have been sighted prior to the set and the net is voluntarily set in their vicinity) or incidental (when individuals have not been seen prior the setting of the net). Hence the term "bycatch" will be used in this thesis for non-targeted species or sizes (i.e. under-sized targeted species) that have been captured and brought on deck 1.12). These individuals may afterwards be either kept onboard as by-product of the fishery or discarded at sea (dead or alive). Likewise, we will consider as discard any

animals i) brought onboard or ii) encircled and released with the crew assistance, that have 1.12). Generally, there is a lack of accurate abundance estimates, as well as rates of bycatch and interactions with purse-seine fishery assessments for cetaceans and whale sharks in most oceans (the EPO is the exception for cetaceans). Therefore, mitigation and conservation measures to reduce mortality, if needed, are very limited. For instance, the IOTC has recently (September 2013), prohibited the intentional setting of purse-seine nets on whale sharks and cetaceans (IOTC res. 13/03 and 13/05). In lack of quantitative data and recognizing their vulnerability, this measure was precautionary.

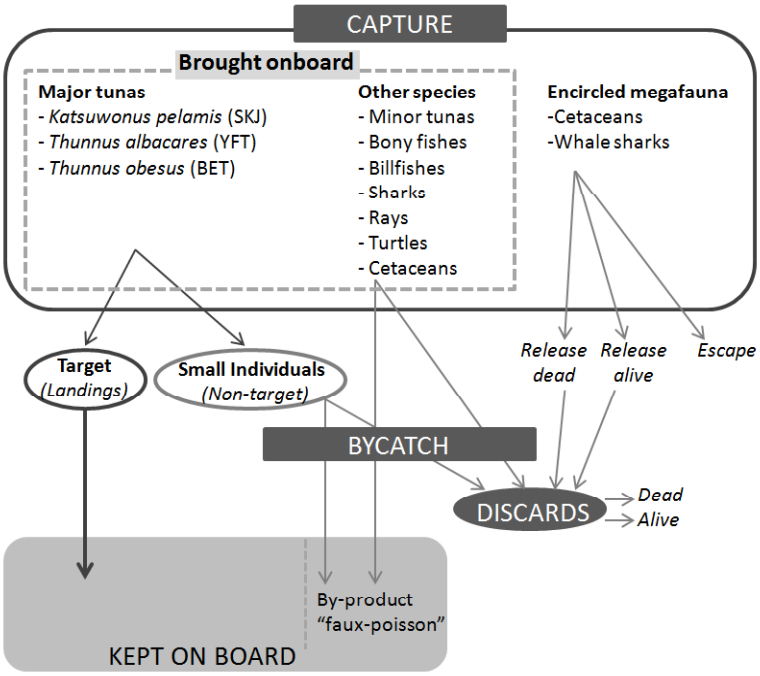

Figure 1.12 Conceptual scheme defining the terms used in the present study and describing the Amandè *et al.* 2012).

1.5a) is a filter feeder and the largest chondrichthyan with a maximum recorded length of 20m (Chen et al. 1997). Studies are still lacking on its biology and ecology. Nonetheless, its size at maturity has been estimated at around 8–9m Rowat and Brooks 2012 Hsu *et al.* 2014). Its distribution covers all the tropical and warm temperate marine regions (preferred temperature of 26.5–30° Sequeira *et al.* 2012). However, the species has been mostly observed as juvenile (predominantly male), with several known feeding aggregation sites worldwide (e.g. Seychelles, Maldives, Western Australia, Red Sead, Carribean Sea, Baja Meekan *et al.* 2006 Nelson and Eckert 2007 Rowat *et al.* 2009 Riley *et al.* 2010 de la Parra Venegas *et al.* 2011 Berumen *et al.* 2014). Recently, the sightings of adult

whale sharks, including pregnant females, have also been made in few places worldwide (i.e. Ketchum *et al.* 2012 Ramirez Macas *et al.* 2012 Acuña-Marrero *et al.* 2014 Afonso *et al.* 2014). Their pelagic distribution and population connectivity has also started to be investigated Castro *et al.* 2007 Sequeira *et al.* 2013b), which indicated a global meta-population. In some aggregation sites, a general decrease in Theberge and Dearden 2006 Bradshaw *et al.* 2008). This decline is mainly caused by over-fishing and will likely be also observed in every sighting sites considering the general connectivity between populations. The principal threat Rowat and Brooks 2012). Before 1990, there was little market for whale sharks' products and they were only caught by artisanal fishery. Yet such exploitation of local populations was considered to affect abundance and these fisheries started to be banned (i.e. 1995 in the Maldives). In the 1990s, the high demand for whale shark flesh (i.e. "tofu shark") in Taïwan lead to the development of fisheries in Philippine, Rowat and Brooks 2012). During this decade, around 1000 individuals were recorded to be captured each year in these fisheries. The catch then declined until a complete ban of killing whale sharks in these countries in 2000, 1998 and 2008, respectively. While whale sharks' fins have been found not suitable for soup, the value of these fins for display purpose have kept increasing over the years and illegal fishing is still occurring Rowat and Brooks 2012). Globally, the whale shark was listed as "Vulnerable" by the IUCN since 2000 but has recently been listed as "Endangered" in june 2016 and has also been included in Appendix II of the CMS in 2000 and in Appendix II of the CITES in 2003.

Concerning cetaceans, most of the sets associated with them in the EAO and WIO 1.5 b to e). The species present in the tropical EAO and WIO are fin whale, sei whale, Bryde's whale, minke whale, humpback whale, and blue whale *Balaenoptera musculus* Budker and Collignon 1952 Robineau 1982 1991 Ballance and Pitman 1998 de Boer 2010 Weir 2011). These species are also mainly planktivorous filter feeders and are found in all oceans. Fin, sei, humpback and blue whales make yearly migrations between summer feeding grounds in the Antarctic and winter low-latitude Weir 2007 Rosenbaum *et al.* 2009). On the other hand, Bryde's whale has been documented to be present year-round in tropical Weir 2007 Anderson 2014), such as along the coast of Gabon to Angola, with most Weir 2007). In the south Atlantic Ocean, there are Best 2001). The first is an inshore population present over the continental shelf of South Africa. It is a local non-migrating population, except for a slight northward movement along the coast of South Africa in winter. The second population

is found in pelagic areas from Gabon to South Africa and migrating north in autumn and Best 2001). In the Indian Ocean, a third population of Bryde's whale is found in the south of Madagascar in summer and it migrates northward in winter along the east coast of Madagascar and may go as far as the Seychelles. All these species have been captured by the whaling industry and the historical records give interesting information on their distributions and migrations. Whales were either captured in their summer feeding grounds in the Antarctic above 40°S (IWC reports archive.iwc.int) or directly in their winter breeding grounds. Therefore in the EAO catches of blue, sei, fin, and humpback whales Budker and Collignon 1952). The humpback whale was the most sought species (up to 1500 individuals captured per year) due to its costal breeding Rosenbaum and Collins 2004). The three other species were considered to have a more pelagic winter distribution, but sei whale also appeared to present a differing behaviour. Unlike the other species that do not feed during the breeding period, this one was often observed feeding on small schooling fishes in Gabonese waters Budker and Collignon 1952). In the WIO, humpback whales were caught in coastal areas of Robineau 1982 Wray and Martin 1983). Fin, sei, blue and Bryde's whale were also captured in this ocean but mostly in a large area from the African Coast to the Seychelles (15°S–0°N), as well as in the southern part of the Ocean (40–30° Robineau 1982). In both oceans, populations of baleen whales for the northern hemisphere are also present. For instance humpback whale, as well as presumably the other species, have winter (January–May) mating and calving grounds in Cape Verde, which was Hazevoet and Wenzel 2000 Bamy *et al.* 2010 Hazevoet *et al.* 2011). In the WIO, Arabian Sea populations of non-migrating baleen whales, Robineau 1982 Mikhalev 1997 Clapham and Ivashchenko 2009 Anderson *et al.* 2012 Bettridge *et al.* 2015). Finally, nowadays, all these baleen whale species has been listed ("Endangered", "Vulnerable" or "Least Concern") by the IUCN and have been included in Appendix I or II of the CMS and in Appendix I of the CITES.

1.3.4 The tropical tuna datasets

Several datasets from the European tropical purse-seine fishery can be combined to assess the above topics and address lacks mentioned. Details on the datasets used for each 1.13 gives an overview of all the tropical tuna databases. The French and Spanish datasets used are collected by the Institut de Recherche pour le Développement (IRD), and the Instituto Espagñol de Oceanografía (IEO), for logbooks and onboard observers, and AZTI Tecnalia,

for onboard observers.

Firstly, logbooks are reported by captains onboard purse-seiners. It was implemented in the 1960s, but detailed records for each fishing set have been recorded since 1980. Logbooks are systematically filled, including the fishing mode since 1990. All fishing sets are recorded with the date, time, position, the possible sighting cues and the tuna catch by species and size category. In addition, when no fishing set is performed, the position at midday, the main activity of the day and any indices of tuna presence (sightings cues) are 1.13).

Secondly, as the species composition may be biased by captains (i.e. due to misidentification between juvenile of yellowfin and bigeye tunas or the overestimation of the proportion of skipjack in the small size tuna commercial category) a sampling procedure is undertaken by scientists at landing sites to correct the species composition by commercial size category (Species database). During the landing, tuna are sampled, identified and measured. These species and size composition estimates are then used to correct the declarative logbook 1.13 and Chapter 5 for details). While this corrected dataset includes precise species and size composition, only the two main fishing modes: FAD (including whale shark associated set) and free school (including whale associated set) sets are used. In addition, for statistical purposes the catch species composition has been homogenized over large time-area strata, and does not reflect the Pallarés and Petit 1998).

Finally, the scientific observer dataset has been widely used in the thesis. Scientific observer programs have been implemented with the main objectives of assessing and monitoring bycatch. They were conducted within the framework of specific EU research projects in the 1990s, and within continuous data collection programs since 2003 (EU Data Collection Framework, Regulation [CE] 199/2008). The coverage rate was historically low (i.e. <10%) but has increased since 2014 (100% in the EAO and 40% in the WIO). Each record includes date, time, position, and information on possible indices for the presence of tuna schools (sightings cues). These records are made for each fishing set with also the tuna catch, the bycatch, as well as the fate of the individuals captured. In addition, a record is made either for each new activity (e.g. searching, going toward an observed cue, seeding a FAD) or every hour when the activity has not changed.

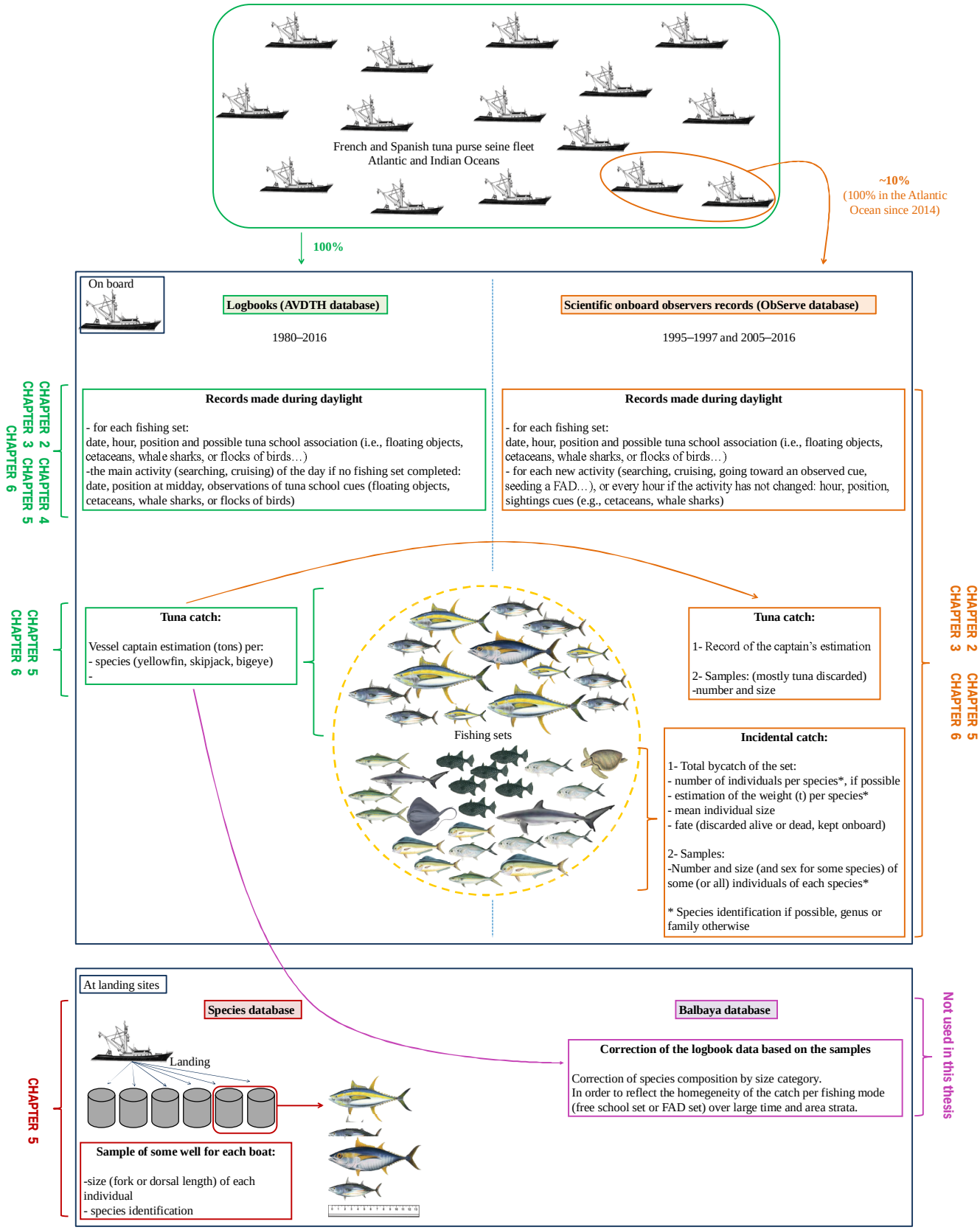

Figure 1.13 Schematic representation and description of the European tropical tuna purse-seine databases and the correction procedure of the information declared in the logbooks by the sampling at landing.

1.4 Objectives and structure of the thesis

Despite the general recognition of the need for an Ecosystem Approach to Fisheries management, there is still a lack of study on the interactions between the tuna purse-seine fishery and megafauna species and the assessment of fishery impact on these species. In the tropical tuna purse-seine fishery, the stocks of exploited species are monitored and bycatch Amandè *et al.* 2010 2012). However as the setting on whale and whale shark associated tuna schools are less frequent, information on megafauna associated fishing sets in the EAO and WIO were little and fragmented before proposing this thesis project. To date, no dedicated studies have been performed on the co-occurrence (i.e. the fact that they both occur in space and time) and interactions (i.e. the fact that animals are directly in contact with the fishery and therefore potentially caught, which may influence their fate) between whale shark, cetaceans and the tuna purse-seine fishery. In addition, fisheries are currently looking for certification, therefore correct estimates of purse-seine fishery interactions with megafauna, as well as the species caught in association with whale shark and cetaceans is pursued. For all of these reasons, throughout five chapters and a general discussion, this thesis aims to fill these gaps by studying the different aspects of these relationships in a conservation perspective.

Chapter 2 describes the interactions between whale sharks and the tuna purse-seine fishery in the EAO and WIO (article 1). It therefore involves the definition of the interaction's context (i.e. intentional or incidental setting around whale sharks), their quantification and mapping. Within an EAF, the identification of main spatio-temporal areas of co-occurrence and interactions could help define conservation management measures, if needed. From scientific onboard observers and satellite tagging data (article 2), the fate of encircled individuals is also investigated. Consequently we estimate the apparent and first results of post-encirclement survival rates. Then, based on these observations a safe release method for whale sharks encircled by tuna purse-seine nets is proposed. Overall, this chapter aims to define the spatio-temporal interactions between whale shark and the tuna purse-seine fishery and tentatively assess the impact of the fishery on whale sharks' populations.

Likewise, the co-occurrence and interactions between cetaceans and the tuna purse-seine fishery in the EAO and WIO are analyzed in Chapter 3 (article 3). First the group of species (baleen whale, delphinid or sperm whale) involved are identified, as well as the species that are most likely concerned. As for whale shark, the co-occurence or interactions, including the context, is quantified for each group, as well as the main spatio-temporal areas are identified. Finally the fate of encircled individuals is explored allowing for the assessment of apparent survival rates. Overall, this chapter aims to define the spatio-

temporal co-occurence and interactions between the tuna purse-seine fishery and cetaceans and estimate the potential impact of the fishery on their populations.

Thereafter, we considered possible environmental determinism to potentially being linked to the spatio-temporal co-occurrences observed. Therefore, in Chapter 4, the interactions between whale shark and cetaceans (separately) and the tuna purse-seine fishery is investigated in relation to environmental variables (article 4). Species included in the two megafauna groups are filter feeders and may therefore be attracted to highly productive area, characterized for instance by chlorophyll-a concentration. In addition, other factors such as STT, distance to the continental shelf and eddies may also influence directly their distribution or indirectly through the distribution of their prey. This chapter aims to identify environmental variables that may be linked to the spatio-temporal distribution of the co-occurrence between the purse-seine fishery, whale sharks and cetaceans.

Then, it was evident that not only single species interacting with the fishery, but also possible inter-specific association should also be investigated. The main objective of Chapter 5 is therefore to explore the species assemblage caught under whale sharks and baleen whales. In Chapter 5, the species captured in association with whale sharks and baleen whales in tuna purse-seine nets is studied (article 5). This involves the assessment of the catch composition of targeted tunas, in terms of species and size spectrum, in whale and whale shark associated sets. In addition, the biodiversity of bycatch (life-stage and species compositions) captured in these fishing modes is also investigated. These two aspects are respectively compared to results from free school and FAD sets, as well as between oceans. Consequently, this chapter aims to characterize the species composition and size spectrum of targeted species, as well as bycatch diversity in whale and whale shark associated sets in the EAO and WIO.

Finally, in an EAF management perspective, side effects of conservation and management measures should be investigated. In the purse-seine fishery, this may appear through changes in fishing strategy and distribution, leading to modifications in the tuna catch, bycatch and number of megafauna associated sets. Therefore, in Chapter 6, the potential collateral impacts of conservation and fishing effort regulation measures for the purse-seiners are investigated (articles 6 and 7). This represents fishing effort management measures (no-take zone, or FAD moratorium) entered into force in the past or still in effect today, as well as the simulation of potential new regulations on FAD-fishing. The consequences of these regulations on whale shark and cetaceans are assessed. Then, the other way round is also simulated, with potential conservation measures (bans of setting on whale sharks and cetaceans) in the main areas of interactions previously identified. Therefore the consequences that may have these measures on the fishing strategy and the reallocation of

effort distribution of the European purse-seine fleet on the tuna catch, amount of by-catch for the main groups, and number of sets on megafauna is investigated. Hence, the aim of this chapter is to identify possible side effects that may arise following conservation or management regulations in an EAF management perspective.

Ultimately, in the general discussion (Chapter 7), other aspects that may also influence conservation of whale shark and cetaceans, such as key reproduction areas and populations abundances, are discussed. The bycatch of other megafauna species (sharks, rays, turtles), especially of species at risk of extinction, is then presented. This therefore leads to a discussion on the several aspects of megafauna conservation in the purse-seine fishery and how these have or could be accounted for by tRFMOs in an EAF management. Likewise, as whale sharks and cetaceans are also interacting with the purse-seine fishery in other tropical regions (EPO and WCPO), the current knowledge regarding this topic in these oceans is presented. Thus, the lack of data is also highlighted, leading to the identification of studies that should be undertaken in these oceans. Generally, the main contributions as well as the limits of this thesis are presented, and the main objectives for future studies are identified. Lastly, the general conclusion highlights the outcome of this thesis and the contribution to the EAF in the purse-seine fishery within a conservation of megafauna species perspective.

The second chapter of this thesis, dealing with the co-occurrence and interactions between whale sharks and the tuna purse-seine fishery, is divided into two different parts. Firstly, the spatio-temporal variability in these co-occurrence and interactions were explored using both scientific onboard observer and logbook databases. In addition, the apparent impact of the fishery on whale sharks has been assessed using observer database. Nevertheless it was evident that whale shark post-release survival on the longer term should also be investigated. Therefore, a satellite tagging experiment was secondly proposed and performed in the course of a field trip at sea as an onboard scientific observer during the main period previously identified of the highest rates of whale sharks encirclement. In addition, an improvement of the whale shark "safe release" method was presented, as well as the first results from our tagging experiment. While the sample size was too low to assess whale shark post-release mortality in the purse-seine fishery yet, these methods could be reproduced in other regions and oceans to provide estimation of whale shark post-release survival rate by this fishery.

Chapter 2

Interactions between whale sharks and the tuna purse-seine fishery.

Part 1. Mortality of marine megafauna induced by fisheries: insights from the whale shark, the world's largest fish

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Published in Biological Conservation (Article 1)

Capietto, A., Escalle, L., Chavance, P., Dubroca, L., Delgado de Molina, A., Murua, H., Floch, L., Damiano, A., Rowat, D., Merigot, B. (2014) Mortality of marine megafauna induced by fisheries: insights from the whale shark, the world's largest fish. Biological Conservervation doi: 10.1016/j.biocon.2014.03.024

Abstract

The expansion of human activities is endangering megafauna in both terrestrial and marine ecosystems. While large marine vertebrates are often vulnerable and emblematic species, many are considered to be declining, primarily due to fisheries activities. In the open ocean, certain fisheries improve their efficiency of detecting tuna schools by locating and fishing close to some macro-organisms, such as whale sharks or cetaceans. However, collecting accurate data on the accidental capture and mortality of these organisms is a complex process. We analyzed a large database of logbooks from 65 industrial vessels with and without scientific observers on board (487 272 and 16 096 fishing sets since 1980 and 1995 respectively) in both the Atlantic and Indian Oceans. Distribution maps of Sightings Per Unit of Effort highlight major hotspots of interactions between the fishery and whale sharks in the coastal area from Gabon to Angola in the Atlantic from April to September, and in the Mozambique Channel in the Indian Ocean between April and May. The incidence of apparent whale shark mortality due to fishery interaction is extremely low (two of the 145 whale sharks encircled by the net died, i.e. 1.38%). However, these two hotspots presented a relatively high rate of incidental whale shark capture. Thus, we underline the importance of estimating long-term post-release mortality rates by tracking individuals and/or by photographic identification to define precise conservation management measures.

Key words

Apparent survival; bycatch; hotspots of interaction; marine conservation; megafauna; *Rhincodon typus*

2.1 Introduction

The rapid expansion of human activities threatens megafauna in both terrestrial Schipper *et al.* 2008 Hoffmann *et al.* 2010). While the oceans encompass habitats of some of the earth's largest species and longest evolutionary history, there is increasing evidence of declines in populations of large marine vertebrates, including those of little or no commercial value such as marine mammals, sharks, rays, sea turtles Lewison *et al.* 2004 Read *et al.* 2006 Wallace *et al.* 2011 Dulvy *et al.* 2014 Senko *et al.* 2014a). These declines can potentially impact ecosystem functioning, including Ferretti *et al.* 2010 Estes *et al.* 2011), Gilman 2011). In addition, the recovery of these species may be difficult due to delayed life history features (e.g. late maturity, low fecondity, long life-spans).

In light of these declines, attention has focused on the ecological impacts of bycatch (i.e. catches of non-targeted species) in fisheries, which are emerging as the principle threat Polidoro *et al.* 2008 McClenachan *et al.* 2012), especially for rays and Stevens *et al.* 2000 Simpfendorfer and Kyne 2009 Ferretti *et al.* 2010). Few explicit quantitative studies have estimated accidental capture and mortality induced by fisheries, Lewison *et al.* 2004 Moore *et al.* 2013). Indeed, many at-risk vertebrate species live in the open ocean, making surveys expensive and difficult to undertake. In addition, the large spatial scales that fishing fleets and pelagic organisms cover make accurate assessments complex. Such quantification is, however, an important challenge in the frame of the EAF, which strives to apply an integrated approach to fisheries, taking into account ecosystem components (biotic, abiotic, human) and their Christensen and Maclean 2011).

To improve their efficiency in the fairly homogenous open ocean, tropical tuna purse-seine vessels actively search for signs that can indicate the presence of tuna schools Dagorn *et al.* 2013). Tuna often aggregate under floating objects such as drift-wood, artificial FADs (i.e. bamboo rafts), or associate with large marine species (e.g. whale shark, Romanov 2002 Dagorn *et al.* 2013). Fishing close to such macro-organisms, even sometimes involuntarily, can lead to their accidental capture and potentially impact Hall 1998 Rowat and Brooks 2012).

The whale shark (*Rhincodon typus*, Smith 1828) is the world's largest living chon- Rowat and Brooks 2012) and is an emblematic and sensitive species. It is listed as Vulnerable by the IUCN (www.redlist.org), in Appendix II of the CMS (www.cms.int), and is included in Appendix II of

the CITES (www.cites.org). The species has a circum-global distribution and occurs in all Rowat and Brooks 2012). Although some studies have investigated the distribution of whale shark sightings and Sequeira *et al.* 2012 2014), little is known regarding their interactions with fisheries or fate when inciden- Rowat and Brooks 2012 Rowat *et al.* 2009). RFMOs and non-governmental environmental organizations have thus underlined the need to scientifically quantify these impacts.

In this context, the aims of this study were to i) update the spatio-temporal location of hotspots of interactions between tuna purse-seine fisheries and whale shark considering complementary fishing fleets and years in the eastern Atlantic and western Indian Oceans (EAO and WIO) ii) document the number and fate of encircled animals (mortality or apparent survival when released).

2.2 Materials and methods

Since the start of the European tropical tuna fishery in the early 1960's in the EAO and 1980's in the WIO, the French and Spanish components (presently 23 and 42 purse-seine vessels) have been monitored by the IRD, and the IEO and AZTI Tecnalia, Fonteneau 2009 2010). For both oceans we analysed two principle data types to complementarily assess the impact of fisheries, each with their own advantages and Lewison *et al.* 2004): i) logbook declarations of fishing vessels completed by skippers, and ii) data from scientific observer programs (i.e. "data collection plans in which independent observers collect data aboard fishing vessels on catch of target and bycatch species"). While observer coverage may be low relative to the total fishing effort, owing to the cost of such programs and the need for well-trained observers, they provide the highest Lewison *et al.* 2004).

Logbooks contain declarative data for 31-years (1980–2011) covering nearly 100% of the French and Spanish fleets in both oceans (captured by IRD and IEO, respectively). We define an "activity" as a record declared by skippers with: i) geographic position, ii) fishing set characteristics (time and catch composition) and iii) association information (e.g. whale shark sighting). If no fishing set is made during the day, one record is registered at midday with geolocation and association information if any. Additionally, observer data contain scientific observations and provide location and fate of whale shark in case of capture (apparent survival or immediate mortality when released). French (IRD) and Spanish (AZTI and IEO) observer datasets span 16 years between 1995 and 2011, with coverage low relative

to logbook data (approximately 10% of fleet activities). Observations are recorded during all fishing days (day time hours) for each modification in activities (e.g. new clue identified, fishing set, FAD operations). When no modification in activity occurred, one record is made each hour; any sighting made when not fishing (e.g. ship cruising) is also recorded. Spatio- 2.1). An interaction between the fishery and a whale shark is defined as any whale shark sighting (e.g. observation during ship cruising, fishing activities) and any individual caught (i.e. encircled by the net), with mortality or apparent survival recorded.

Table 2.1 Comparison of sightings reported by captains and observers respectively within the same trips from the French tuna purse-seine fleet in the Atlantic and Indian Oceans.

	Logbook dataset (1995–2011)	**Observers dataset (1995–2011)**		
333 French fishing trips	**Total**	**Capture**	**Observation**	**Total**
Whale shark sightings	25	25	28	53
Sightings registered in one dataset	4	7	25	32
Sightings registered in both datasets[1]	21	18	3	21
% of common sightings in both datasets[1]	84.0	72.0	10.7	39.6

[1](sightings at same date, hour and position)

Due to variability in hydro-climatic factors that may drive both whale shark and fishery distributions, each year was divided into different periods for each ocean. In the EAO, we considered four trimesters starting from January (numbered 1–4). For the WIO, we defined two main monsoons periods [north-east (NE) from December to March (1) and south-west (SW) from June to September (3)], and two inter-monsoons periods [south-west (ISW), April-May (2) and north-east (INE), October-November (4)].

In order to produce accurate maps of interaction hotspots, we used a Poisson krig- Goovaerts 2005 Monestiez *et al.* 2006) to take the spatial heterogeneity of observation effort into account and computed Sightings Per Unit of Effort (SPUE, i.e. number of whale shark sightings per fishery activities). Kriging parameterizations were carefully performed (Appendix 2.A). Note that mapping of SPUE by kriging could not be performed in [1] nor for each season separately due to low sighting numbers precluding 2.1). All analyses were conducted using the R software (version 2.15.2, R Development Core Team 2013).

[1]while not directly located in the study areas of this thesis, this region also presented some European purse-seine fishing activities in the 1980s and 1990s.

2.3 Results

In the logbook dataset 468 181 activities were registered in the EAO with 6673 whale shark sightings. Similarly, a total of 393 404 activities were registered in the WIO with 2142 whale shark sightings. In the observer dataset, there were 169 546 activities registered in the

2.2 for main data characteristics).

Table 2.2 Main statistics of logbook and scientific observers datasets on the French and Spanish tuna purse-seine fishery in the eastern Atlantic Ocean (EAO) and western Indian Ocean (WIO).

	Logbook dataset (1980–2011)			**Observer dataset (1995–2011)**		
	EAO	**WIO**	**Total**	**EAO**	**WIO**	**Total**
Number of activities[1]	468 181	393 404	861 585	169 546	114 581	284 127
Number of whale shark sightings	6 673	2 142	8 815	198	90	288
% whale shark sighting among activities	1.43	0.54	1.02	0.12	0.08	0.10
Number of fishing sets	238 172	249 100	487 272	9 969	6 129	16 096
% Sets among activities	50.87	63.32	56.56	5.88	5.35	5.67
Number of whale shark associated to a fishing set	6 613	2 040	8 653	134	47	181
% whale shark associated with fishing sets	99.10	95.24	98.16	67.68	52.22	62.85
% Sets with whale shark associated	2.78	0.82	1.78	1.34	0.77	1.12
% Sets with whale shark caught				1.07	0.55	0.88
Number of sets with whale shark caught				107	34	141
Number of whale shark caught				111	39	150
% whale shark catch by sightings				56.06	43.33	52.08
Number of whale shark fate known				107	38	145
Number of whale shark apparent survival				106	37	143
% whale shark apparent survival				99.07	97.37	98.62

[1]An activity is a record made during vessel's action (e.g. during fishing, ship cruising). A whale shark associated with a fishing set is a sighting during fishing activity; a capture is a whale shark actually encircled by the net.

The whale shark sightings declared by skippers in both oceans were located in 2.1), with a matching of hotspots of fishery and whale shark interactions when based on absolute sightings or standardized by fishing effort (whale 2.2.a). Areas presenting high SPUE are concentrated in the eastern part of the Gulf of Guinea in the EAO, and in the Mozambique Channel in the WIO. Although

2.1), the high number of fishing activities in this area accounted for the low SPUE.

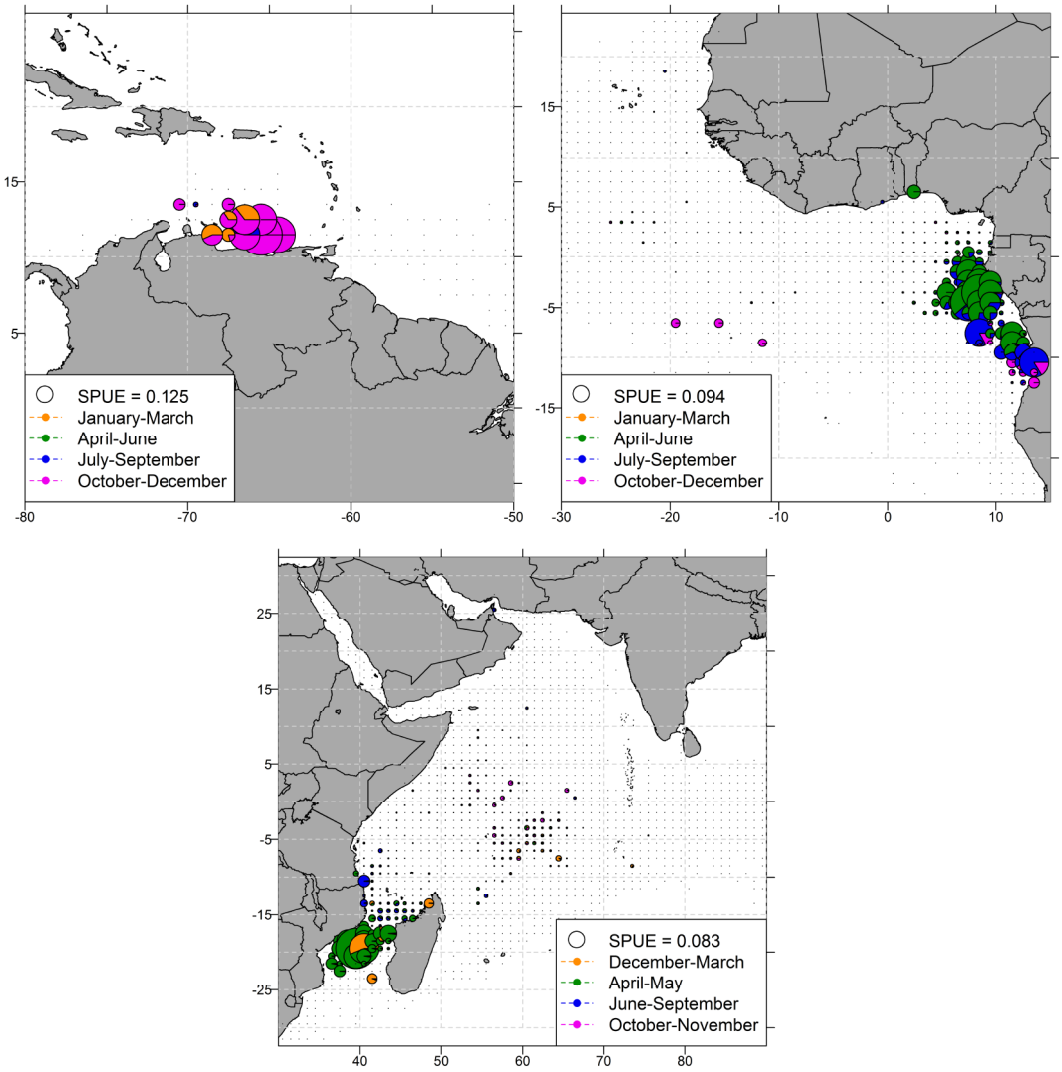

Figure 2.1 Seasonal distribution of whale sharks SPUE (Sightings Per Unit of Effort) by 1° square from 1980 to 2011 a) in the west (Caribbean), b) east of the Atlantic Ocean (Africa), and c) in the Indian Ocean (source logbook data).

In the EAO, 77% of whale shark sightings were concentrated in the Gulf of Guinea, 2.1). In the Caribbean Sea, whale shark observations were concentrated between October and December (189 sightings), but mostly occurred in a single year (2008, 127 sightings). In the WIO, whale shark sightings were particularly high in the Mozambique Channel during the ISW monsoon (1 115 sightings) and to a lesser extent in a 10° square east of Seychelles (from 0°N–10°S and 55°E–65°E) during the NE and INE monsoons (815 sightings). A more northerly distribution was also detected during the SW monsoon, but related to fewer observations (212 sightings).

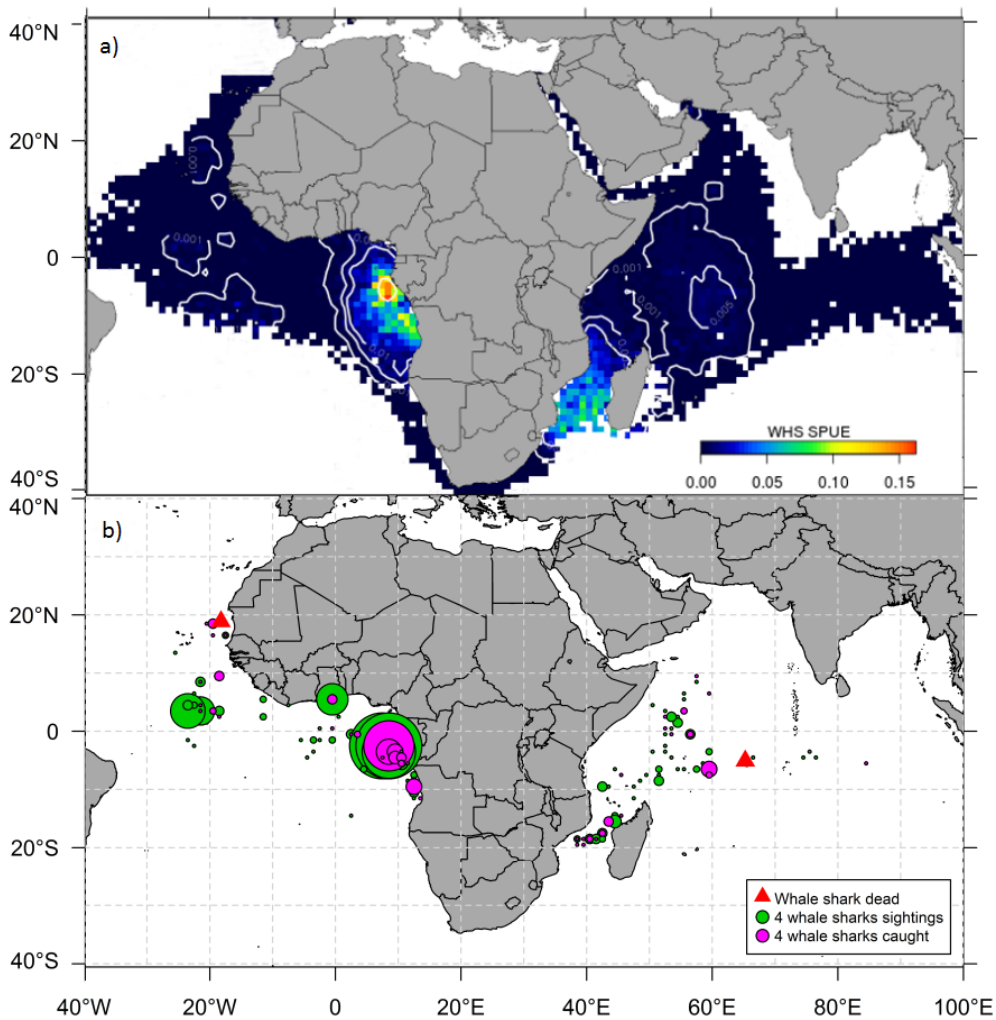

Figure 2.2 a) Distribution maps of Sighting Per Unit Effort (SPUE) of whale sharks in the Atlantic and Indian Oceans from 1980 to 2011 (logbook data) estimated using Poisson kriging. b) Distribution of observations, catches and mortality of whale sharks in the Atlantic and Indian Oceans from 1995 to 2011 (scientific observers' data).

According to the scientific observer dataset (available in the overall study area but excluding the Caribbean Sea), the rate of whale shark sighting during all recorded activities is very low (0.1%); whereas the percentage of whale shark sighting during fishing activity (1.12%) as well as the capture of whale shark (0.88%) in fishing sets are around 1% in both 2.2). The immediate impact of fishing on apparent whale shark mortality was low in both oceans. In the EAO, one case of whale shark mortality from 107 records of known 2.2.b, 2.2). In the WIO, one mortality in 38 records of known fate was reported in the east 2.2 2.2). In other capture events, 25 whale shark escaped from the net alive (16 and 9 in the EAO and WIO, respectively), and 118 were released from the net or removed alive without being brought onboard (90 and 28 in the EAO

and WIO). Thus, observed whale shark apparent survival rate was 99.07% and 97.37% of the whale shark caught in the EAO and WIO, respectively. It is noteworthy that whale shark sightings, capture and apparent survival probabilities were similar between EAO and WIO 2.2).

2.4 Discussion

Hotspots of high frequency of co-occurrence between whale shark sightings and purse-seine fishing were identified during specific periods of time and areas, particularly in the coastal zone between Gabon and Angola from April to September for the EAO, and in the Mozambique Channel during the ISW monsoon (April–May) for the WIO. This is in agreement with previous studies on whale shark distribution focused on French logbooks Sequeira *et al.* 2012 Sequeira *et al.* 2014). Several factors may dictate the spatio-temporal patterns observed. Seasonal distributions could be linked to modifications in the environmental conditions, such as Rowat and Brooks 2012 Sequeira *et al.* 2012). Similarly, reproductive behavior might affect distribution but little is known about whale shark reproductive behavior. In the EAO, the primary interaction area is located between Cape Lopez ($\sim 0°$) and the Angola Benguela Front (10°S) from April to September; corresponding to the local wet season, with significant input of fresh water and dissolved organic substances from rivers into the marine environment (e.g. Ogooué, Congo rivers). Furthermore, the area is characterized by seasonal upwelling from Hardman-Mountford *et al.* 2003). In the WIO, the Mozambique Channel circulation pattern is influenced by anticyclonic gyres Schott *et al.* 2009); current circulations reverse between seasons and the upwelling areas changes from south (January) to north (July), which may drive whale shark movements. The area seems to present suitable characteristic for whale shark, especially during the ISW

Sequeira *et al.* 2012). There is a need for improved knowledge on whale shark migrations in relation to the above environmental factors and potential interactions with fisheries, which Rowat and Brooks 2012). Whale sharks are placid organisms, swimming slowly, and aggregating several species of fishes, including tunas. This feature may be used by purse-seiners to locate tuna, and nets are sometimes set around them, Rowat and Brooks 2012 Dagorn *et al.* 2013). In the Pacific fleets, high whale shark mortality has already been recorded from fishing activities (60 individuals died WCPFC 2010). This prompted management measure from the WCPFC to ban the

WCPFC 2011), implemented at the beginning
IOTC 2013).
These recent management measures have been implemented as precautionary approach because the WCPFC and IOTC consider that whale sharks are vulnerable, ecologically important and emblematic. In addition they admitted that accurate data on the interaction between purse-seine operations and whale shark are lacking. In contrast, in the EAO, ICCAT has not yet proposed any management measures for whale shark.

Our results highlight the very low immediate apparent impact of the purse-seine fishery on whale shark in both the EAO and WIO (0.91% and 2.56% apparent whale shark mortality, respectively). Recently, best practices for the safe release of whale shark have been developed for fishermen when a whale shark is accidentally caught, such as cutting
Poisson
et al. 2014b). The IOTC now requires these guidelines to be followed when a whale shark is accidentally encircled, which should contribute to the maintenance of this high apparent survival rate. It is important to note that the two recorded mortality events occurred outside
2.2.b). However, the
2.2.b). Thus, it
is important to assess the long-term post-release survival of whale shark, in order to produce appropriate fisheries management measures for whale shark conservation, such as a FAD moratorium, prohibiting the intentional setting of nets on whale shark or restricted fishing around these hotspots during the periods identified.

While immediate apparent survival rates of whale shark in European purse-seine fishery were based on the scientific observers' dataset, which only cover 10% of this fleet, there are plans to increase this coverage to 100% by 2016 (since July 2013 coverage has already increased to 50%). In addition, even though improved coverage will provide more data interactions and health status at the time of release, investigating the effective post-capture survival rates for longer periods remains essential. This would be feasible through satellite tracking, using Pop-Up Satellite Archival Tags (considering the practical constraints of tagging a whale shark at surface when the fishing set is ended and most tunas have been removed from the net, and by approaching the whale shark from the purse-seiner speedboat under calm conditions). Similarly, photographic identification could be used alongside, using
Arzoumanian *et al.* 2005). Overall, collecting and analyzing both logbooks, observers, electronic tagging and photo-ID data would strengthen fishery impact studies and help define conservation management for marine megafauna.

Acknowledgements

We thank two anonymous reviewers for their constructive comments on the manuscript. We are grateful to fishing masters and observers involved in data collection, to fishing companies and TAAF (Terres Australes et Antarctiques Françaises) for their close collaboration with European fishery scientists (IRD/IEO/AZTI). Collection of logbook data is supported by French and Spanish National Fisheries Administration and Observer programs are co-financed by the European Data Collection Framework and Scientific Institutions (IRD, IEO and AZTI). We thank P. Cauquil, C. Rodriguez (IRD), S. Rodriguez (IEO), J. Ruiz (AZTI) for valuable database support, and P. Dewals (IRD) for conducting interviews with skippers. We are also grateful to participants of Ecosystems working groups of ICCAT and IOTC for their comments. D. Rowat and J. D. Filmalter have corrected the English of the paper.

Part 2. Post-capture survival of whale sharks encircled in tuna purse-seine nets: tagging and safe release methods.

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Published in Aquatic Conservation (Article 2)

Escalle, L., Murua, H., Amandé, J. M., Arregui I., Chavance, P., Delgado de Molina, A., Gaertner, D., Fraile, I., Filmalter, J. D., Santiago J., Forget F., Arrizabalaga H., Dagorn L., Mérigot, B. (2016) Post-capture survival of whale sharks encircled in tuna purse-seine nets: doi: 10.1002/aqc.2662

Abstract

1. Whale shark, the world's largest fish, is believed to be particularly vulnerable due to its biological characteristics (slow growth, late maturation, high longevity) and is listed by IUCN and CITES.

2. Whale sharks are occasionally encircled in tropical tuna purse-seine nets, throughout this global fishery. Although apparent immediate survival rates following encirclement and release have recently been assessed through scientific onboard observer programs, a more rigorous methodology is still required for studying post-released survival.

3. This work provides a method for applying pop-up satellite tags and reports an enhanced release procedure for whale sharks. The first assessment of survival after release from purse-seine nets involved six whale sharks tagged between May and September 2014 in the eastern tropical Atlantic Ocean. Five tags transmitted data: three popped up as programmed (after 30 days), while two surfaced prematurely (one after 21 and the other after 71 days (programmed to pop off after 30 and 90 days)) but showed no sign of unusual behaviour.

4. Overall, whale sharks survived at least 21 days (one at least 71 days) after release from purse-seine nets. These observations based on five large individuals (total length > 8 metres), suggest that whale sharks have a good chance of survival when released with the proposed method.

5. Additional tagging in this and other oceans, especially of juveniles which may be more sensitive to encirclement and release operations, is essential to further assess whale shark post-release survival rates in tuna purse-seine fisheries.

Key words

Megafauna, post-release mortality, PSAT, *Rhincodon typus*, tropical tuna purse-seine

2.5 Introduction

With a maximum recorded length of 20 metres (m) the whale shark (*Rhincodon typus*, Smith 1828) is the world's largest living chondrichthyan and its spatial distribution Rowat and Brooks 2012). This filter Wilson *et al.* 2006 Brunnschweiler *et al.* 2009) where it feeds on pelagic invertebrates (e.g. krill, shrimp eggs, copepods) or small Rowat and Brooks 2012). Due to its biological characteristics, such as slow growth rate, late maturation (∼20 years) and high longevity (more than 70 years), the whale Rowat and Brooks 2012 Hsu *et al.* 2014). As such, the whale shark is listed as Vulnerable by the IUCN (www.redlist.orgwww.redlist.org), is included in Appendix II of the CMS (www.cms.int), and in Appendix II of the CITES (www.cites.org).

Tunas are known to often aggregate around floating objects (natural or artificial) or Dagorn *et al.* 2013). As a result, whale sharks are sometimes encircled in the nets of tropical tuna purse-seine vessels (average of 6.6 ± 7.8 (standard deviation) individuals reported as encircled per year between 1995 and 2011, data from French and Spanish scientific observers programs, covering about 10% Capietto *et al.* 2014). This is sometimes an involuntarily result, as fishers may not notice the whale shark before setting Capietto *et al.* 2014). On rare occasions they can detect the whale shark at the surface of the sea and consequently may intentionally set around it in order to catch the associated tuna school, where this practice is not forbidden, such as in the EAO. Consequently, the impact of tuna purse-seine fisheries on the whale shark populations Rowat and Brooks 2012 Capietto *et al.* 2014).

A previous study based on the French and Spanish scientific observer programs showed that the apparent immediate mortality of whale shark from European purse-seiners' net is very low (i.e. 0.93 and 2.53% for the 1995–2011 period in the EAO and WIO, re- Capietto *et al.* 2014). However, the need to accurately quantify the post-release mortality rates to assess the impact of the purse-seine fishery on these large animals has Capietto *et al.* 2014). While, some tRMFOs, e.g. IOTC, WCPFC, and IATTC, have prohibited the intentional setting of nets on whale sharks since September 2013 (IOTC Res[13/05]), January 2014 (WCPFC, CMM-2012-04), and July 2014 (IATTC, Res[C-13-04]); respectively, the ICCAT has not yet banned setting nets on whale shark. Poisson *et al.* 2014b) and WCPFC has drafted (WCPFC 2014) handling practices for purse-seine vessels to release whale sharks that have been

accidentally encircled by their nets, but these practices need further detailed description and [2].

Considering the lack of data on post-release survival of whale sharks following encirclement in tuna purse-seine nets, the aims of this study were to, i) describe a tagging method from fishing vessels, ii) report a method for the safe release of whale shark encircled by purse-seine nets, and iii) provide the first observations on post-release survival.

2.6 Materials and methods

2.6.1 Tagging procedure

Satellite tagging is commonly used in ecological studies of highly migratory species Eckert 2006 Gore *et al.* 2008 Hueter *et al.* 2013 Witt *et al.* 2014 Capietto *et al.* 2014) such as the whale shark. Whale sharks have previously been equipped with either pop-up archival tags or real-time tethered tags placed below the first dorsal fin or using a collar fixed on this fin. Generally, tagging has been performed either on free swimming Wilson *et al.* 2006 Brunnschweiler *et al.* 2009 Hueter *et al.* 2013), or on individuals caught by traditional Hsu *et al.* 2007). In the current study these methods were not appropriate as it was unsafe for scientific observers to dive in the net and the use of a spear gun or a Hawaiian-sling at the surface carried too high a risk. As such, an appropriate tagging procedure from the deck of a purse-seine vessel was developed for scientific observers. While similar tagging methods have already been used for other Witt *et al.* 2014), the fact that it has to be performed by one scientist onboard a professional fishing vessel induced particular features (constraints with a purse-seine net, varying position of the whale shark, long distance between the deck and the animal). Tagging was conducted onboard French and Spanish purse-seiners in the EAO between May and September 2014; the period identified as having the highest whale shark sightings and encirclements events Capietto *et al.* 2014).

Pop-up archival tags (miniPATs, Wildlife Computers, USA) were used as they can provide information on the movements of fishes that rarely break the surface and also provide depth data used to determine the vertical behaviour from which the condition and fate of the

[2]The method roughly described by Poisson et al. (2014) consists in placing a rope under the whale shark, if its head points toward to bow of the vessel, to help the animal stand on the float line and then roll outside the sack.

animal can be determined. In addition, ambient light levels, used to estimate geographic position, and water temperature are also recorded. After a pre-programmed deployment duration, the tags detach from the animal and come to the surface where the archived data are transmitted via the Argos satellite system. Since the objective of this study was to assess the post-release survival of whale sharks after encirclement and releasing operation, pop-up tags were programmed to detach 30 (5 tags) or 90 (1 tag) days after deployment. Additionally, miniPATs were equipped with a pressure sensitive guillotine, which ensures the tag detached when depth exceeded approximately 1800 m, to prevent hydrostatic damage to the tag. Given Brunnschweiler *et al.* 2009 Hueter *et al.* 2013), a tag severing at this depth may indicate a dive below 1800 m or death of the individual, which may be discriminated using the descent speed. Furthermore, tags were programmed to initiate a release when no change in depth (±2.5 m) occurred for a 72-hour period (i.e. to detect mortality in waters shallower than 1800 m).

Six whale sharks that were accidentally encircled by purse-seiners were tagged. Tagging was performed at the end of the fishing operation, when the whale shark was in the sack (i.e. prior to the release procedure). Tagging was only possible when the whale shark was parallel to the vessel, with the dorsal fin visible at the surface. Tagging was 2.3.a) fitted with a 14 cm (from the tip to a stopper, which was used to limit deeper penetration of the anchor) titanium tag applicator (Wildlife Computers, USA). Pop-up archival tags were externally attached to whale sharks using a titanium anchor, connected to the tag with an 18 cm tether (270 lb stranded steel line covered with heat-shrink tubing), which was implanted 2.3.a). Total length (TL; 8–12 m for the tagged 2.3) of each shark was estimated using reference marks on the deck and thereafter measured to the nearest 0.5 m. Sex was visually determined, when possible, by the presence or absence of claspers.

Table 2.3 Summary information of the six whale sharks tagged in the Atlantic Ocean.

Shark no.	Tag no.	Tagging date	TL[a] (m)	Sex[b]	Latitude[c]	Longitude[c]	Pop-up date	Latitude[d]	Longitude[d]	Tracking duration[e]
1	14P0118	29/06/14	8.0	F	2°50 S	8°20 W	08/09/14	3°32 S	1°22 W	71
2	11P0095	03/07/14	11.0	F	2°49 S	8°07 W	02/08/14	2°10 S	8°06 W	30
3	11P0122	05/07/14	12.0	-	2°41 S	8°29 W	04/08/14	1°50 N	4°96 W	30
4	11P0285	24/07/14	8.5	F	1°42 N	3°17 W	23/08/14	0°49 S	1°46 E	30
5	11P0283	24/07/14	10.0	F	1°50 N	3°36 W	14/08/14	2°53 N	9°86 E	21
6	10P0458	24/07/14	8.5	F	1°45 N	3°23 W	-	-	-	-

[a] Total length. [b] "F" = Female, "-" = Sex unknown. [c] Tagging location. [d] Corresponding to the position of the first Argos data transmitted. [e] Pop-up programmed date 90 days after tagging for shark no.1, 30 days for the others.

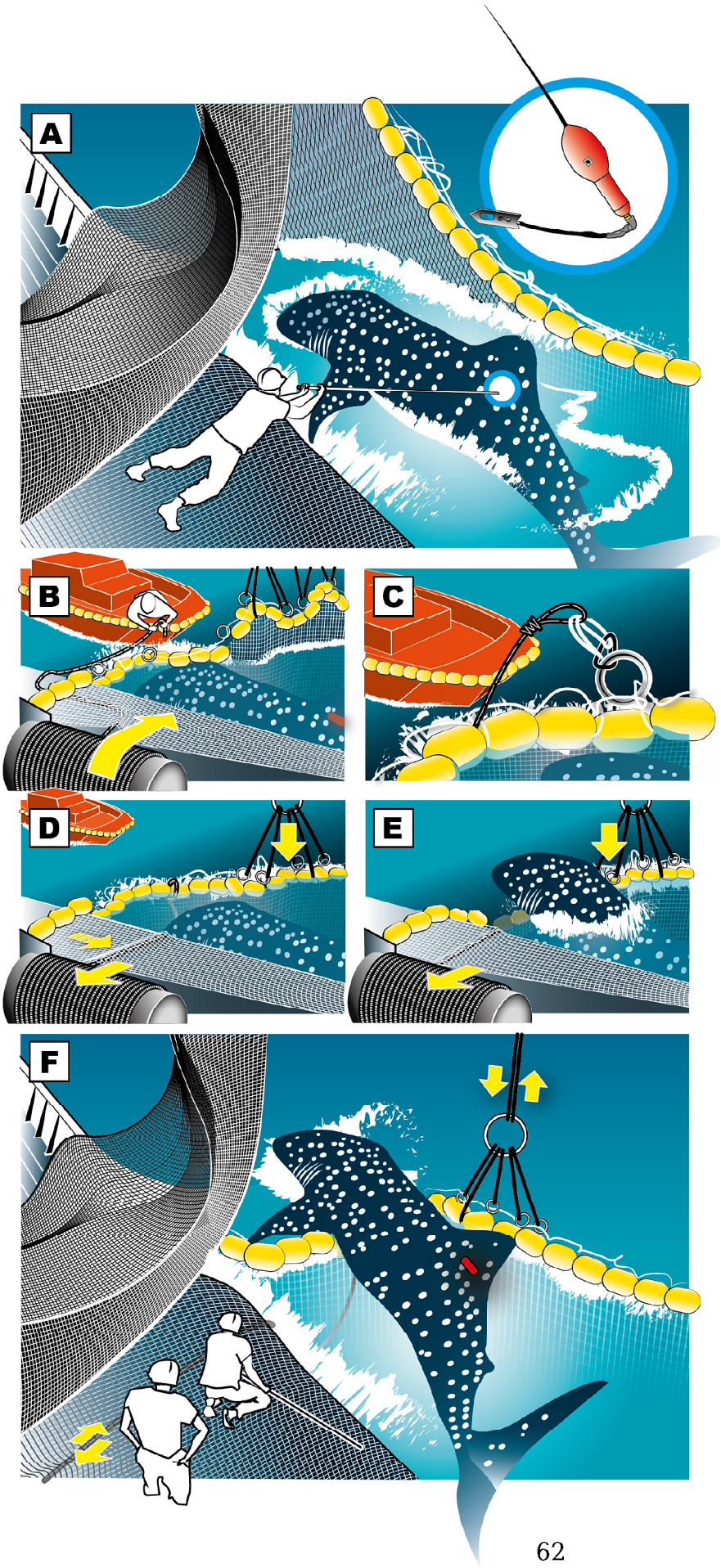

Figure 2.3 Tagging and release of a whale shark from an encircling purse-seine net 1.4 for a general view of the vessel and the position of the net upon release of the whale shark during these procedures). a) Tagging at the surface with a pop-up archival tag using a 4-metre tagging pole, b) to f) Handling practice to release a whale shark from the net, observed in the Atlantic Ocean. b) A cable fed through and out of the net on the deck is passed, around of the net, to a crew member in the speedboat, c) the cable is then attached to one of the cork sack rings close to the whale shark's head, d) the cork line is slacked from the brailing boom, and the cable is tightened so that it slip along the gunwale while being under tension and positions itself underneath the sack below the whale shark's head, e) as the cable continues to be tightened, the cork line is pulled down, causing the whale shark's head to roll over the float line, which sinks with the whale shark's weight. f) The whale shark rolls over the float line when alternating between pulling and slaking the cable underneath the sack and the cork line (from the brailing boom).

2.6.2 Release procedure

Once tagged, the following method for the safe release of whale sharks was applied Poisson *et al.* 2014b). Whale sharks were usually released from the sack after most of the tuna had been [3] onboard, in order to prevent major loss should the net have broken during the release procedure. Thus, the duration during which the whale shark was constrained in the sack varied from 30 minutes (min) to 1h10. The release procedure lasted from 5 to 20 min. The overall time between the beginning of the set and the whale shark release ranged from 1h35 to 3h30. If the position of the whale shark was perceived to be good (at the surface, parallel to the vessel and not in a vertical orientation in the sack) the crew released the individual 2.3 b to f). Alternatively, if the position of the whale shark in the sack made it difficult or impossible to carry out this procedure, the crew either cut a portion of net (see below) or inverted the sack after brailing most tuna onboard (not observed during this study).

The safe release method observed was achieved by placing a cable underneath the entire sack containing the whale shark. The cable was fed through and out of the net on the deck and passed, on the outside of the net, to a crew member in the speedboat adjacent to 2.3.b). The crew member then proceeded to attach the end of the cable to 2.3.c). The crew then slackened 2.3.d). The cable was then tightened so that it slipped along the gunwale while being under tension and positioned 2.3.d). When required, the crew in the speedboat helped to position the cable underneath the sack. As the cable was tightened further, the cork line was pulled down, causing the whale shark's head to roll over 2.3.e). Finally, with its head out the sack, the crew alternated between pulling and slacking the cable and the cork line (from the 2.3.f).

This method was used irrespective of the orientation of the whale shark in the sack in the horizontal plane (head towards the bow or the stern). However, when the shark was 2.3), it was first released before any tuna was brailed, by cutting a few metres of net horizontally in front of the sharks' head, allowing it to swim out. The duration during which the whale shark was constrained in the sack varied from 30 minutes (min) to 1h10. The release procedure lasted from 5 to 20 min.

[3] Brailing refers to the process of boarding tuna onboard the purse-seiner using a large dip net called brail. This may take few minutes to more than an hour depending on the catch.

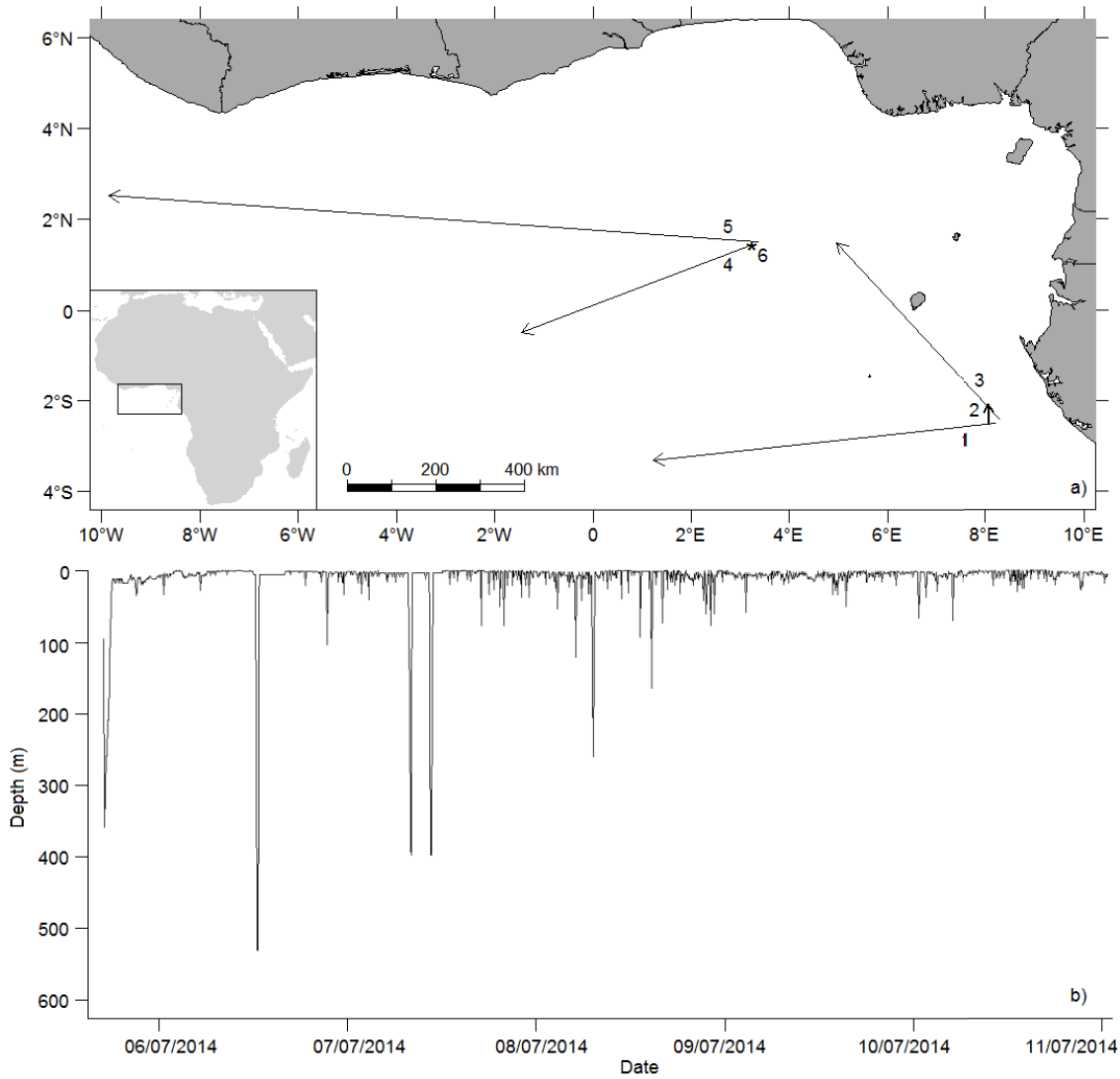

Figure 2.4 a) Map of whale shark tagging and released pop-up locations in the Atlantic Ocean. Numbers represent the tagging location of each shark (the star represents the tagging location of the individual (no. 6) with the tag that did not report), and arrows represent the straight line distance between tagging and pop-up locations, b) Depth profile during the first week following tagging for the whale shark no. 2 tagged on the 05/07/14.

2.7 Results

2.3;

the sex of the last individual could not be determined). One of the tags did not transmit, and this tag was not included in the analysis as no conclusion can be drawn regarding the fate of this individual. Three tags popped-up on the programmed date, 30 days after deployment, and two tags detached prematurely after 21 and 71 days (programmed deployments of 30 and 90 days, respectively). Therefore, it can be assumed that 5 sharks survived at least 21 days after release. The reason for the premature detachment 71 days after tagging is unknown.

The second premature detachment, 21 days after tagging, occurred after a deep dive (last recorded depth below 1800 m), and is thus likely the result of mechanical guillotine release to avoid hydrostatic damage to the tag. The descent speed during this last dive was of 55.6 metres/minute (m/min) which is similar to the mean descent speed of the other tagged whale sharks: 49.9 ± 10.7 m/min (dives deeper than 800 m).

The tagging (6 individuals) and pop-up (5 individuals) locations (first Argos data 2.4.a. While the pop-up location of the second shark was very close to the tagging location (i.e. 70 km), the other four sharks showed large movements during the 3–7 week tracking periods (from 560 km in 30 days to nearly 1500 km in 21 days for shark no. 5), which also reinforce arguments toward surviving sharks. All sharks undertook dives deeper than 800 m and all but one shark dived close or below the tags' maximum limit of 1800 m. An example of the vertical behaviour displayed by a whale shark 2.4 Wilson *et al.* 2006 Brunnschweiler *et al.* 2009, for similar vertical behaviour). It was also noted that all sharks dived immediately after tagging and release (up to 360 m), before returning to the surface waters after approximately 1h40 (± 30 min).

2.8 Discussion

While being cautious with the generalization of this statement based on five tagged whale sharks, this study suggests that large whale sharks released from tuna purse-seine nets using the proposed safe release method have a good chance of post-release survival. Historically, whale sharks have sometimes been towed out of the net by the skiff or a purse-seiner's cable using a rope attached to their caudal fin. These release methods may affect survival dues to injuries caused by the manipulation of heavy animal. European tuna vessel Poisson *et al.* 2014b) have thus required the use of safe release methods. However, even when these are applied, long-term impacts of encirclement, such as increased stress or non-apparent injuries which may play a role in chronic mortality, have not yet been assessed.

Among the five tags that reported, one whale shark survived at least 71 days, and four individuals survived at least 21 or 30 days after being encircled by a purse-seine net. Concerning the premature detachment 71 days after tagging, while its cause cannot be determined, such premature tag detachment has been previously reported with pop-up Musyl *et al.* 2011). This can be induced when the tag tears out after being bitten by other animals or infection around the anchor, or tether failure which may be accelerated by biofouling or several deep dives. For the second premature

detachment after 21 days, even if the fate of this shark cannot be determined with certainty, the similar descent speed between the last recorded dive and the four other whale sharks' deep dives tends to indicate that it was a normal deep dive and not the shark sinking after dying. Finally, the non-reporting pop-up may be due to one of a number of reasons such as tag failure (software, release mechanism, battery failure), or transmission failure (i.e. tag or Musyl *et al.* 2011).

It should be noted that all the whale sharks tagged were females larger than 8 m and thus, considered to be adult or sub-adult individuals when assuming size at maturity ≥ Rowat and Brooks 2012 Hsu *et al.* 2014). From visual estimation by scientific observers it was shown that most whale sharks encircled by purse-seine nets in the EAO were large individuals (75% of whale sharks encircled in 2014 were larger than 8 m (±1 m)), but some smaller individuals were also recorded (minimum recorded size of 0.7 m off Mauritania) (unpublished data from the French scientific observers program). As these smaller individuals could be more sensitive to encirclements and release operations, their post-release survival should also be investigated in the future.

In the Atlantic Ocean, while no ICCAT measure regulates whale sharks encirclements, recently, European purse-seiners have generally begun to follow the handling practices for Poisson *et al.* 2014b). Here, details for an enhanced method applied by the fishing crew were reported, which should help its replication by describing each step of the procedure. This method requires fishermen to use the speedboat. However it does not affect the crew safety or the duration of the procedure, while it increases the safety for the whale shark, by having the cable placed under the sack instead of directly under its body.

Overall, this study represents a first step to investigate whale shark post-release survival from tuna purse-seine nets across the world oceans. The proposed tagging method can easily be performed by scientific observers onboard purse-seiners. As such, the tagging of additional individuals, including juveniles, should be pursued worldwide, such as in the Pacific and Indian Oceans, to assess whale shark post-release survival rates in tuna purse-seine fisheries. While using commercial vessels and existing scientific observer programs, such study could also help access whale shark oceanic behaviour and movements which are Rowat and Brooks 2012). This would allow to identify more precisely Queiroz *et al.* 2016), and spatio-temporal Mazor *et al.* 2016). In a context of an EAF, assessing impacts of tuna purse-seine fishery on vulnerable megafauna is essential and may help define, if needed, conservation management measures.

Acknowledgements

We thank the Editor Prof. John Baxter and an anonymous Reviewer for their constructive comments on an earlier version of the manuscript. The authors are grateful to the scientific observers involved in data collection; the fishing masters, crew and their fishing companies for their collaboration in this experiment. L. Escalle is funded by a PhD grant from the University of Montpellier. The pop-up tags were funded by the ORTHONGEL-IRD project on bycatch mitigation (financed by the DPMA and EU) and CalvoPesca S.A. fishing 2.3. This paper is contribution no. 764 from AZTI (Marine Research Division).

Appendix 2.A

Poisson kriging method and parameterizations.

Method

Mapping whale shark abundance requires the interpolation of sightings data related to fishery activities on a 1° square grid covering the two oceans. As whale shark sightings may be recorded during fishing sets and also during other vessel activities, the variable "activity" was assumed to depict the most accurate unit of effort. We thus computed sightings per unit of effort (SPUE), which represents the number of whale shark sightings divided by the total number of purse-seiner activities (i.e. fishing activities and transit) recorded in Sequeira *et al.* 2012 Goovaerts 2005 Monestiez *et al.* 2006) to account for the spatial heterogeneity in the observation effort. Indeed, whale shark sighting rates calculated for areas in which fishing activities are low will be less reliable than those calculated for densely fished areas. The Poisson kriging method Goovaerts 2005 Ali *et al.* 2006 Monestiez *et al.* 2006 Kerry *et al.* 2010). We present below a summary of the method Monestiez *et al.* 2006).

For all sites s (1° squares) belonging to the domain D (in our case the EAO and WIO), $z(s)$ is the number of whale shark sightings and $t(s)$ is the number of fishing activities for the corresponding sites. The observed SPUEs are calculated as $y(s) = z(s)/t(s)$. At each site s, the sightings $z(s)$ can be interpreted as a realization of a random variable $Z(s)|Y(s)$. This variable follows a Poisson distribution (P) with an intensity parameter (the expected number of sightings) that is the product of the number of fishing activities $t(s)$ and the SPUE $Y(s)$:

$$Z(s)|Y(s) \sim P(t(s)Y(s)) \tag{2.1}$$

where $Y(s)$ is a positive random field following order two stationarity, with mean m, variance σ_Y^2 and a covariance function which depends only on the distance h between sites s and s': $C_Y(h)$ Monestiez *et al.* 2006), the notations were simplified; therefore, $Z(s)$, $Y(s)$ and $t(s)$ are denoted by Zs, Ys and ts.

The kriging of Y_0, at any site $s_0 \epsilon D$, is a linear predictor combining the n neighboring observed sightings z_i, weighted by the number of fishing activities t_i:

$$Y_O* = \sum_{i=1}^{n} \lambda_i \frac{Z_i}{t_i} \tag{2.2}$$

λ_i is computed to minimize the mean square error of predictions under the constraint that the estimator is unbiased. The kriging weights are the solution of the following system of the $n+1$ linear equation:

$$\sum_{j=1}^{n} \lambda_j C_{ij} + \lambda_i \frac{m*}{t_i} + \mu = C_{I0}, i \epsilon [1, n] \tag{2.3}$$

$$\sum_{i=1}^{n} \lambda_i = 1 \tag{2.4}$$

where λ is the Lagrange multiplier, $m*$ is an estimate of the mean of Y, and C_{ij} denotes the covariance function $C_Y(i-j)$. The covariance function of Y is equivalent to its variogram $\gamma *_Y (h) = C_Y(0) - C_Y(h)$. The experimental semivariogram $\gamma *_Y (h)$ is estimated from the data by:

$$\gamma_Y * (h) = \frac{1}{2N(h)} \sum_{i,j} (\frac{t_i t_j}{t_i + t_j} (\frac{Z_i}{t_i} - \frac{Z_j}{t_j})^2 - m*) 1_{d_{ij} \sim h} \tag{2.5}$$

where $1_{d_{ij} \sim h}$ is the indicator function of pairs (s_i, s_j) whose distance is close to h, where $N(h) = \sum_{i,j} \frac{t_i t_j}{t_i + t_j} 1_{d_{ij} \sim h}$ is a normalizing constant and where $m*$ is an estimate of the mean of Y. A model $\gamma Y(h)$ is then fitted to $\gamma *_Y (h)$ in order to derive the semivariogram for any possible distance h Monestiez *et al.* 2006) pp. 618-621

Goovaerts 2005) pp. 8.

Table 2.A.1. Nested fitted variogram parameters.

Ocean	Varioram	Sill	Range (km)
EAO	Nugget	3.91e-5	-
EAO	Gaussian	5.41e^{-5}	175
EAO	Gaussian	1.86e^{-4}	2636
WIO	Nugget	2.08e^{-4}	-
WIO	Gaussian	1.93e^{-3}	594

The experimental variograms for the entire logbook datasets were computed for

each ocean (Figure 3.1). Initially, we checked that no directional effect was present in the experimental variograms. Then we fitted the variogram models to the experimental variogram using a weighted least-square regression procedure. The nested semivariogram models selected were two Gaussian variogram models for the EAO, and a Gaussian variogram model for the WIO. Nugget models were also added for each ocean. For each model, the sills and distance range were calculated (Table 2.A.1). The input parameters used to conduct the kriging included a minimum of one and a maximum of 32 observations and a radius of 1000 km.

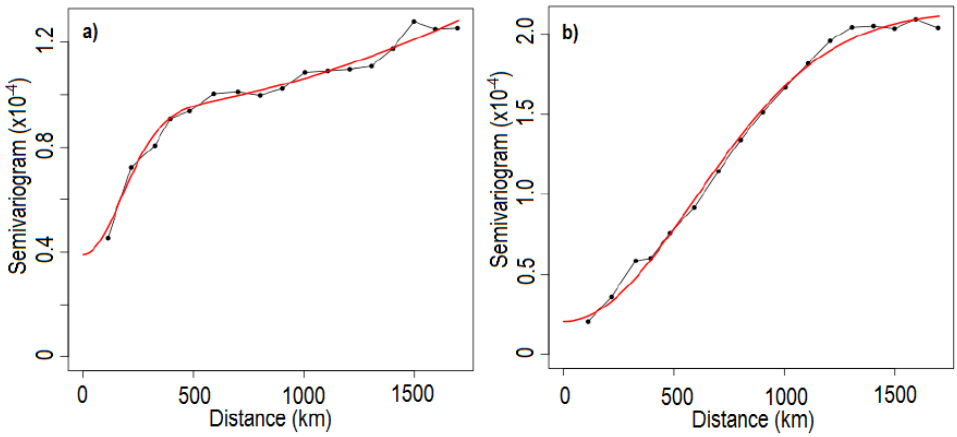

Figure 2.A.1. Experimental (black dots and black line) and fitted (red line) semivariograms from the a) eastern Atlantic Ocean (weighted residual sum of squares: 2.8e^{-4}) and b) western Indian Ocean (weighted residual sum of squares: 3.91e^{-9}).

It was not possible to separately map SPUEs by season or cetacean group as the low numbers of sightings precluded the computation of the experimental variogram (see 2.1 for SPUEs maps). All analyses were conducted using R software (version 2.15.2, Monestiez *et al.* 2006).

Appendix 2.B

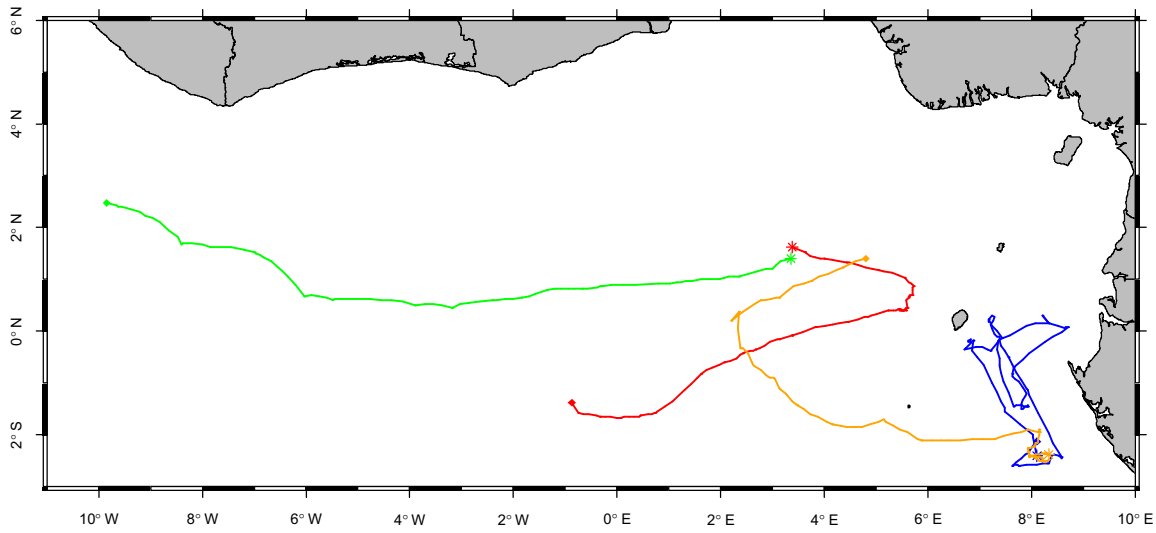

Figure 2.B.1. Detailed movements of the whale sharks tagged by the French team in the Atlantic Ocean in 2014 (position derived from wildlife computers position correction procedure): sharks no. 2 (blue; considering maximum speed of 9 km/h), no. 3 (yellow; 7 2.3. Stars indicate tagging position and dots pop-up locations.

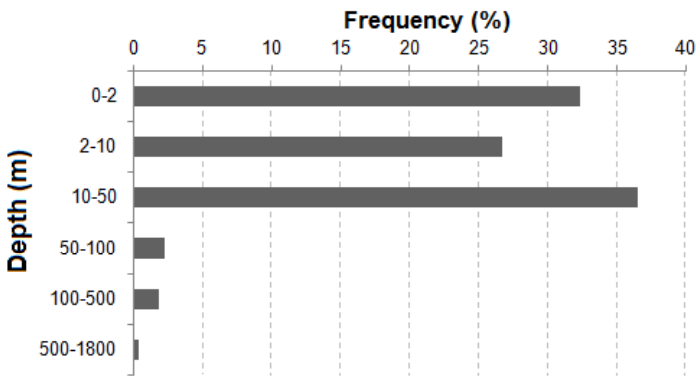

Figure 2.B.2 Average time spent at depth of the four whale sharks tagged by the French team in 2014 in the Atlantic Ocean (sharks 2 to 4).

In the previous chapter, the spatio-temporal co-occurrence and interactions between whale sharks and tuna purse-seine fishery, as well as impacts of this fishery on the species, have been investigated. It should be emphasized that whale sharks have been mostly recorded in both logbook and observer datasets during fishing sets and are often encircled. Therefore they can be considered to directly interact with the purse-seine fishery. Concerning whale shark longer term post-encirclement survival rates, tagging of additional individuals is pursued, which will also allow investigating movements outside fishing areas. Hence experienced scientific onboard observers were then trained to perform additional tagging during following years (no tagging in 2015 due to few encirclements but five individuals have been tagged in June 2016). To complement results presented in Chapter 2, detailed movement of the four whale sharks tagged in 2014 by the French team was investigated (Appendix 2.B) but this should be studied more deeply when more individuals have been tagged. In addition, time spent at different depths was examined (Appendix 2.B) in order to estimate the proportion of time spent by whale sharks in the first meters of the epipelagic zone and thus where they can potentially be encircled by purse-seiners. Based on four large individuals (8.5 m < TL < 12 m), over a mean period of 28 days (± 2.5), it was found that whale sharks spend 95% of their time above 50 meters, but only 30% in the surface (0–2m), which may explain why whale sharks are often not detected before the setting of the net. For cetaceans, knowing their breathing dependence to the surface, it is unlikely that they would not be detected before setting. In the Atlantic and Indian Oceans, cetaceans may also be, as for whale sharks, another megafauna group interacting with the purse-seine fishery and could thus potentially also get encircled. Hence, in the following chapter, spatio-temporal interactions and/or co-occurrence between cetaceans and the purse-seine fishery, as well as potential impacts of the purse-seine fishery will be investigated. It will be explored for the different cetaceans groups (e.g. baleen whales or dolphins), and species if possible, as this may vary depending on the one considered.

Chapter 3

Interactions and/or co-occurrence between cetaceans and the tuna purse-seine fishery.

Cetaceans and tuna purse-seine fisheries in the Atlantic and Indian Oceans: interactions but few mortalities

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Published in Marine Ecology Progress Series (Article 3)

Escalle, L., Capietto, A., Chavance, P., Dubroca, L., Delgado De Molina, A., Murua, H., Gaertner, D., Romanov, E., Spitz, J., Kiszka, J.J., Floch, L., Damiano, A., Merigot, B. (2015) Cetaceans and tuna purse seine fisheries in the Atlantic and Indian Oceans: interactions but

doi: 10.3354/meps11149

Abstract

Fisheries bycatch is considered to be one of the most significant causes of mortality for many marine species, including vulnerable megafauna. In the open ocean, tuna purse-seiners are known to use several cetacean species to detect tuna schools. It exposes them to encirclement which can lead to incidental injury or death. While interactions between fishers and cetaceans have been well documented in the eastern tropical Pacific Ocean, very little is known about these interactions and potential mortalities in the tropical Atlantic and Indian Oceans. Here, we provide the first study quantifying these interactions in both oceans by analyzing a large database of captain's logbooks (1980–2011) and observations collected by on-board scientific observers (1995–2011). Distribution maps of sightings per unit of effort highlighted main areas of relatively high co-occurrence: east of the Seychelles (December–March), the Mozambique Channel (April–May) and the offshore waters of Gabon (April–September). The percentage of cetacean-associated fishing sets was around 3% in both oceans and datasets whereas 0.6% of sets had cetaceans encircled. Of the 194 cetaceans encircled in a purse-seine net (122 baleen whales, 72 delphinids), immediate apparent survival rates were high (Atlantic: 92%, Indian: 100%). Among recorded mortalities, eight involved pantropical spotted dolphins (*Stenella attenuata*) and three involved humpback whales (*Megaptera novaeangliae*). These high survival rates suggest setting nets close to cetaceans has a low immediate apparent impact on species involved. Our findings will contribute to the development of ecosystem approach to managing fisheries and accurate cetacean conservation measures.

Key words

Apparent survival; bycatch; cetaceans; fishery impact; marine conservation; megafauna

3.1 Introduction

Worldwide, large numbers of many marine megafauna species are declining, includ- Lewison *et al.* 2004 2014 Read *et al.* 2006 Wallace *et al.* 2011 Dulvy *et al.* 2014). A wide range of human activities affect their populations, including direct and indirect harvesting (i.e. bycatch mortality), habitat destruction, ship traffic, pollution, climate change, and non-lethal fisheries interactions. Fisheries bycatch (i.e. the capture of non-targeted species) is considered as one of the main threats, Lewison *et al.* 2004 Schipper *et al.* 2008 Weir and Pierce 2013 Brown *et al.* 2013). Late maturity and low reproductive rates make marine mammals particularly vulnerable to impacts, while their large body sizes, high metabolic and food consumption rates indicate their important roles in the structure and dynamics of marine Bowen 1997). Thus, quantifying their incidental mortality rates is important not only for species-based conservation and management but also understanding their broader Bowen 1997 Estes *et al.* 1998).

In tropical tuna purse-seine fisheries, vessels actively search for clues indicating the presence of tuna schools at the sea surface, including flocks of birds, cetaceans, whale sharks (*Rhincodon typus*), and natural and artificial floating objects, such as drifting FADs (i.e. Ariz and Gaertner 1999 Gaertner and Medina-Gaertner 1999 Hallier and Parajua 1999 Hampton and Bailey 1999 Romanov 2002 Capietto *et al.* 2014). Given the risk of encirclement by nets when fishing close to cetaceans, there is concern Hall 1998 Gilman 2011). In particular, two cetacean groups are known to interact with these fisheries: dolphins and baleen whales. Species interacting with purse-seiners are listed by the IUCN, in Appendix II of the CMS, as well as in Appendix I or II of the CITES.

In the eastern tropical Pacific Ocean (EPO), the pantropical spotted dolphin *(Stenella attenuata*) and the spinner dolphin (*Stenella longirostris*) are known to associate with schools of large-size yellowfin tuna (*Thunnus albacares* Hall 1998 Scott *et al.* 2012). Historically, tuna purse-seine fisheries in this region have provoked unsustainable dolphin mortalities. Indeed, purse-seine vessels chased, then encircled dolphin groups during fishing operations, Hall 1998). In the 1960s and early 1970s, when the practice was the most widespread, dolphin mortality was Hall 1998). However, there has been a 98% reduction of dolphin mortality due to fishing gear modifications and Hall 1998 Schipper *et al.* 2008 Gilman 2011).

In the western tropical Indian Ocean (WIO) and the eastern tropical Atlantic Ocean Levenez *et al.* 1979 Ballance and Pitman 1998), existing studies suggest scarce interactions between dolphins and purse- Levenez *et al.* 1979 Romanov 2002 Weir and Pierce 2013).

In contrast, whale-associated sets (i.e. nets set close to or around one or more baleen whales) are the major interaction between purse-seine fisheries and cetaceans in the western Hampton and Bailey 1999 Molony 2005). A few mortality events have Molony 2005 Gilman and Lundin 2009 WCPFC 2010). While Gaertner and Medina-Gaertner 1999 Romanov 2002 Amandè *et al.* 2010), including a single mortality Romanov 2002), there are no detailed studies investigating the specific whale-tuna associations and the resulting potential impact of purse-seine fisheries on the species involved.

Megafauna associated with tuna schools can be encircled i) intentionally, such as in the EPO, where this is a fishing strategy consisting of chasing and encircling dolphins Hall 1998) or ii) accidentally, as is the case for whale sharks which Capietto *et al.* 2014). In the EAO and WIO, while fishermen practice to keep baleen whales inside purse-seine nets as long as Romanov 2002), no studies have specifically investigated intentional setting of nets in the vicinity of cetaceans.

In view of potential impacts on cetaceans and the lack of data on purse-seiner Lewison *et al.* 2014), this study aims to i) assess the spatial and temporal distributions of cetacean/purse-seine fishery co-occurrence (i.e. regions with high numbers of cetacean observations standardized by the sighting effort), ii) identify and quantify the nature of cetacean observations (e.g. sightings during tuna searches, fishing sets associated with cetaceans and their encirclements), and iii) determine the fate of encircled individuals (i.e. mortality or apparent survival after release).

3.2 Materials and methods

3.2.1 Datasets

The European tropical tuna purse-seine fishery (i.e. France and Spain) began in the Fonteneau 2009 2010). For each of these two regions, we analyzed separately two complementary datasets to assess the impact of fisheries: i) logbook records filled out by vessel captains and ii) data from scientific observers

onboard fishing vessels. While records from these two sources are made on the same vessels and from the same fishing trips (i.e. when an observer is onboard a vessel, logbooks are still filled by captains), the datasets are independent as they come from two different sources (i.e. scientific observers and vessel captains), and present their own advantages and limitations (see below). Logbooks and observer datasets have specific scientific purposes: estimating fishing effort and catch composition of targeted species for logbook data and assessing the amount of bycatch for observer data. Among all the data contained in these datasets, we only used the data that pertained to cetacean/ purse-seine interactions.

First, we analyzed data from logbook records filled by vessel captains for the 1980–2011 period, which covers 100% of all vessel activities since 1990 (90% before 1990) of the French and Spanish fleets (i.e. 23 and 42 purse-seiners, followed by the IRD and the IEO, respectively). Each fishing set is reported in logbooks. If no set is made during daylight hours, the main activity of the day (e.g. the search for tuna or transit between fishing areas) with the geographical position at midday is recorded. Here, we define an "activity" as a record declared by captains. Activities recorded in logbooks include geographical position, information on associations between tuna schools and cetaceans, whale sharks, seabirds, or floating objects, and for each fishing set, weight and catch composition of targeted tuna species. Considering that not all cetacean species occurring in the fishing areas are necessarily associated with tuna schools, there is a bias in using logbooks alone, with some cetacean species less recorded by captains than others. The main uncertainties in this dataset are that i) encirclements are not discriminated from sightings, and ii) the rates at which captains declare sightings are unknown and may vary between captains.

Complementarily, data from scientific observer programs provided more detailed information on purse-seiner activities, catches of bycatch species (numbers and species involved), and discards (if any), and provides the fate of encircled individuals, including cetaceans. Scientific observer programs were conducted within the framework of specific EU research projects in the 1990s or, since 2003, within continuous data collection programs (EU Data Collection Framework; Regulation (CE) 199/2008). We used French (IRD) and Spanish (AZTI Tecnalia and IEO) observer data collected from 1995 to 2011 (9.2 % of total vessel Bourjea *et al.* 2014). In this dataset, "activities" also include fishing activities (fishing sets and searches for tuna schools), transit between fishing areas, and FAD-related operations (i.e. deployment or recovery). All activities are recorded during daylight hours. If the vessel activity does not change within an hour, a new record of activity is systematically filled.

Cetacean sightings are opportunistic and include any detection of one or a group of cetaceans. "Cetacean-fishery interactions" are sightings associated with fishing sets (whether

cetaceans are encircled or not), which are defined as either whale- or dolphin-associated sets. "Sightings during cruising" include sightings during tuna schools search and transit. When cetaceans are encircled, the number of individuals and their fate are recorded by the observer, i.e. mortality (i.e. entangled in the net) or apparent survival (i.e. alive upon release or escape from the encircling net).

During all fishing activities, members of the crew use fixed binoculars (25x150, 20x120) to detect tuna schools. Among other observations of potential indicators of tuna schools, cetacean sightings are recorded by captains and scientific observers. We assumed that captains tended to mostly record cetacean sightings indicating the presence of tuna schools or made during interactions with fishing sets, while at the same time observers record all cetacean sightings. To check the correspondence and accuracy of cetacean sightings reported in the two datasets, a comparison was performed of the sightings recorded by vessel 3.1).

Table 3.1 Comparison of cetacean sightings reported by captains (logbooks) and scientific observers on board within the same trips from the French tuna purse-seine fleet in the Atlantic and Indian Oceans.

333 French fishing trips	**Logbooks (1995–2011)**	**Observers on board (1995–2011)**
% of shared[1] sightings in both datasets	75.29	13.68
% of shared[1] sightings associated with set	85.07	24.44
% of shared sightings during ship cruising[2]	66.67	11.49

[1] Sightings at same date, hour and position
[2] Sightings during tuna searching or transit at same date and position

The identification of cetacean species was not always possible. However, three broad species groups were defined: i) baleen whales (i.e. Bryde's whale *Balenoptera edeni*, fin whale *Balenoptera physalus*, sei whale *Balenoptera borealis*, and humpback whales *Megaptera novaeangliae*), ii) delphinids (i.e. *Stenella spp.*, common dolphin, *Delphinus delphis*, common bottlenose dolphin, *Tursiops truncatus*, rough-toothed dolphin, *Steno bredanensis*, short-finned pilot whale, *Globicephala macrorhynchus*, false killer whale, *Pseudorca crassidens*, melon-headed whale *Peponocephala electra*, and killer whale *Orcinus orca*), and iii) sperm whales (*Physeter macrocephalus*).

In the observer dataset, we used two methods to identify possible intentional setting of nets in the vicinity of cetaceans. First, when cetacean sightings were associated with fishing sets, we checked if these sightings were also recorded during the activity just prior to the set, which would indicate intentional cetacean-associated sets. Second, we calculated the frequency of cetacean sightings preceding a set (French observer dataset). Thus, i) we

selected cetacean sightings not directly associated with a fishing set to avoid double counting, then ii) we calculated the number of cetacean sightings followed by a fishing set within a radius of 2 nautical miles (i.e. the distance between the vessel position at the time of the sighting and the vessel position at the time of the fishing set; 2 nautical miles corresponds to the average distance of cetacean detectability at sea using binoculars recorded in observer data), and iii) we calculated the corresponding frequencies with which fishing sets were made following cetacean sightings compared to the total number of sightings.

3.2.2 Studied regions

Study areas cover the main fishing grounds of the European purse-seiners (including transit between fishing areas) in the EAO (between 30°N to 35°S and 40°W to the African coast) and the WIO (25°N to 35°S and the African coast to 90°E). EAO circulation is influenced by the Benguela, Angola, Guinea and Canary Currents that generate seasonal upwellings Hardman-Mountford *et al.* 2003 Marcello *et al.* 2011). WIO circulation reflects complex interactions of the seasonally alternating Somali Schott *et al.* 2009). Monsoon-generated seasonal Somalian-Arabian upwelling drastically affects productivity of the northern part of the region. The area east of the Seychelles features Hermes and Reason 2008), known as the Seychelles-Chagos thermocline ridge, while the Mozambique Channel has a Schott *et al.* 2009).

As climatic and oceanographic variability may drive the seasonal distribution of both cetaceans and fisheries, we divided the annual data into seasons that were defined differently for each ocean. In the EAO, we considered four quarters (starting from January; identified Schott *et al.* 2009) which includes two monsoon periods (north-east (NE) from December to March and south-west (SW) from June to September) and two inter-monsoon periods (north-east (INE) from October to November, and south-west (ISW) from April to May).

3.2.3 Statistical Analyses

To produce accurate maps of co-occurrence between cetaceans and the tuna purse-seine fisheries, we first computed sightings per unit of effort (SPUE) for each 1° square of the studied areas. As cetacean sightings may be recorded during fishing sets and also during

other vessel activities, the variable "activity" was assumed to depict the most accurate unit of effort. Thus SPUEs are the number of cetacean sightings divided by the total number of Sequeira *et al.* 2012 Capietto *et al.* 2014).

Goovaerts 2005 Monestiez *et al.* 2006) to account for the spatial heterogeneity in the observation effort. Indeed, cetacean sighting rates calculated for areas in which fishing activities are low will be less reliable than those calculated for densely fished areas. The Poisson kriging method addresses this problem by Goovaerts 2005 Ali *et al.* 2006 Monestiez *et al.* 2006 Kerry *et al.* 2010 Monestiez *et al.* 2006).

For all sites s (1° squares) belonging to the domain D (in our case the EAO or the WIO), $z(s)$ is the number of cetacean sightings and $t(s)$ is the number of fishing activities for the corresponding sites. The observed SPUEs are calculated as $y(s) = z(s)/t(s)$. At each site s, the sightings $z(s)$ can be interpreted as a realization of a random variable $Z(s)|Y(s)$. This variable follows a Poisson distribution (P) with an intensity parameter (the expected number of sightings) that is the product of the number of fishing activities $t(s)$ and the SPUE $Y(s)$:

$$Z(s)|Y(s) \sim P(t(s)Y(s)) \tag{3.1}$$

where $Y(s)$ is a positive random field following order two stationarity, with mean m, variance $\sigma^2 Y$ and a covariance function which depends only on the distance h between sites s and s': $CY(h)$ Monestiez *et al.* 2006), the notations were simplified; therefore, $Z(s)$, $Y(s)$ and $t(s)$ are denoted by Zs, Ys and ts.

The kriging of $Y0$, at any site $s0 \epsilon D$, is a linear predictor combining the n neighboring observed sightings zi, weighted by the number of fishing activities ti:

$$Y_O* = \sum_{i=1}^{n} \lambda_i \frac{Z_i}{t_i} \tag{3.2}$$

λi is computed to minimize the mean square error of predictions under the constraint that the estimator is unbiased. The kriging weights are the solution of the following system of the $n+1$ linear equation:

$$\sum_{j=1}^{n} \lambda_j C_{ij} + \lambda_i \frac{m*}{t_i} + \mu = C_{I0}, i \epsilon [1, n] \tag{3.3}$$

$$\sum_{i=1}^{n} \lambda_i = 1 \tag{3.4}$$

where λ is the Lagrange multiplier, $m*$ is an estimate of the mean of Y, and Cij denotes the covariance function $CY(i-j)$. The covariance function of Y is equivalent to its variogram $\gamma * Y(h) = CY(0) - CY(h)$. The experimental semivariogram $\gamma * Y(h)$ is estimated from the data by:

$$\gamma_Y * (h) = \frac{1}{2N(h)} \sum_{i,j} (\frac{t_i t_j}{t_i + t_j} (\frac{Z_i}{t_i} - \frac{Z_j}{t_j})^2 - m*) 1_{d_{ij} \sim h} \tag{3.5}$$

where $1_{d_{ij} \sim h}$ is the indicator function of pairs (si, sj) whose distance is close to h, where $N(h) = \sum_{i,j} \frac{t_i t_j}{t_i + t_j} 1_{d_{ij} \sim h}$ is a normalizing constant and where $m*$ is an estimate of the mean of Y. A model $\gamma Y(h)$ is then fitted to $\gamma * Y(h)$ in order to derive the semivariogram for any possible distance h Monestiez *et al.* 2006) pp. 618-621 Goovaerts 1998) pp. 8.

The experimental variograms for the entire logbook datasets were computed for 3.1). Initially, we checked that no directional effect was present in the experimental variograms. Then we fitted the variogram models to the experimental variogram using a weighted least-square regression procedure. The nested semivariogram models selected were two Gaussian variogram models for the EAO, and an exponential and a Gaussian variogram model for the WIO. Nugget models were also added for each ocean. For 3.2). The input parameters used to conduct the kriging included a minimum of one and a maximum of 32 observations and a radius of 500 km.

It was not possible to separately map SPUEs by season or cetacean group as the low numbers of sightings precluded the computation of the experimental variogram (see 3.2 for SPUEs maps). All analyses were conducted using R software (version 2.15.2, Monestiez *et al.* 2006).

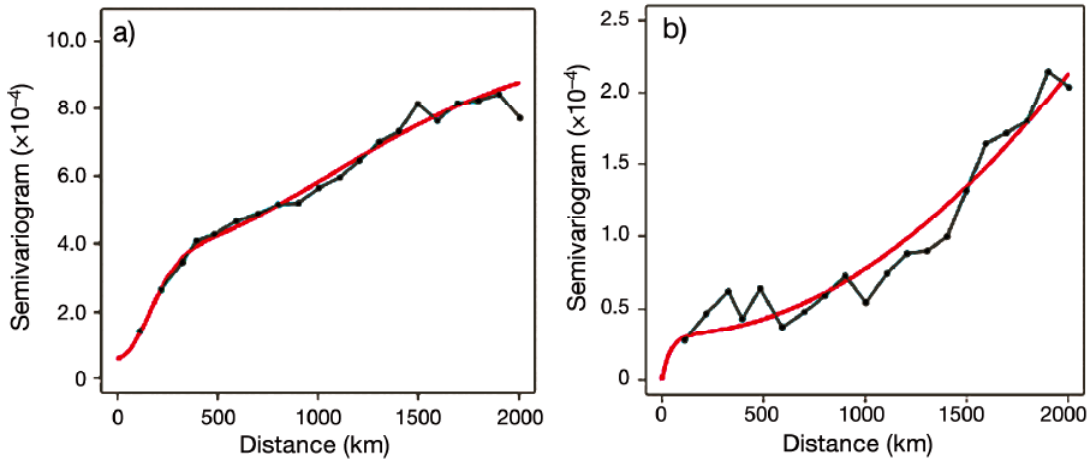

Figure 3.1 Experimental (black dots and black line) and fitted (red line) semivariograms from the a) Atlantic Ocean (weighted residual sum of squares: 4.6e^{-6}) and b) Indian Ocean (weighted residual sum of squares: 2.4e^{-6}).

Table 3.2 Nested fitted variogram parameters.

Ocean	Variogram	Sill	Range (km)
EAO	Nugget	5.98e^{-5}	-
EAO	Gaussian	3.00e^{-4}	151
EAO	Gaussian	6.28e^{-4}	1070
WIO	Nugget	1.00e^{-7}	-
WIO	Exponential	3.15e^{-5}	410
WIO	Gaussian	4.61e^{-3}	7060

3.3 Results

A comparison of cetacean sightings reported in both datasets during the same trip 3.1). About 75% of all sightings and up to 85% of sightings associated with fishing sets declared by captains were also recorded by observers. In comparison, only 14% of all sightings recorded by observers were also found in logbooks (24% for sightings associated with fishing sets only). Overall, onboard observers more frequently reported cetacean sightings than captains, especially sightings during ship cruising (i.e. tuna search and transit).

Of the total 861 585 activities recorded in the logbook dataset, 487 272 were fishing 3.3). This dataset also included 19 003 records of cetacean sightings, most of which were baleen whales (17 802), followed by delphinids (1165) and sperm whales (38). While cetacean sightings were recorded during 2.2% of all activities and 3.1% of all fishing 3.3), almost 80% of all cetacean sightings were associated with fishing sets.

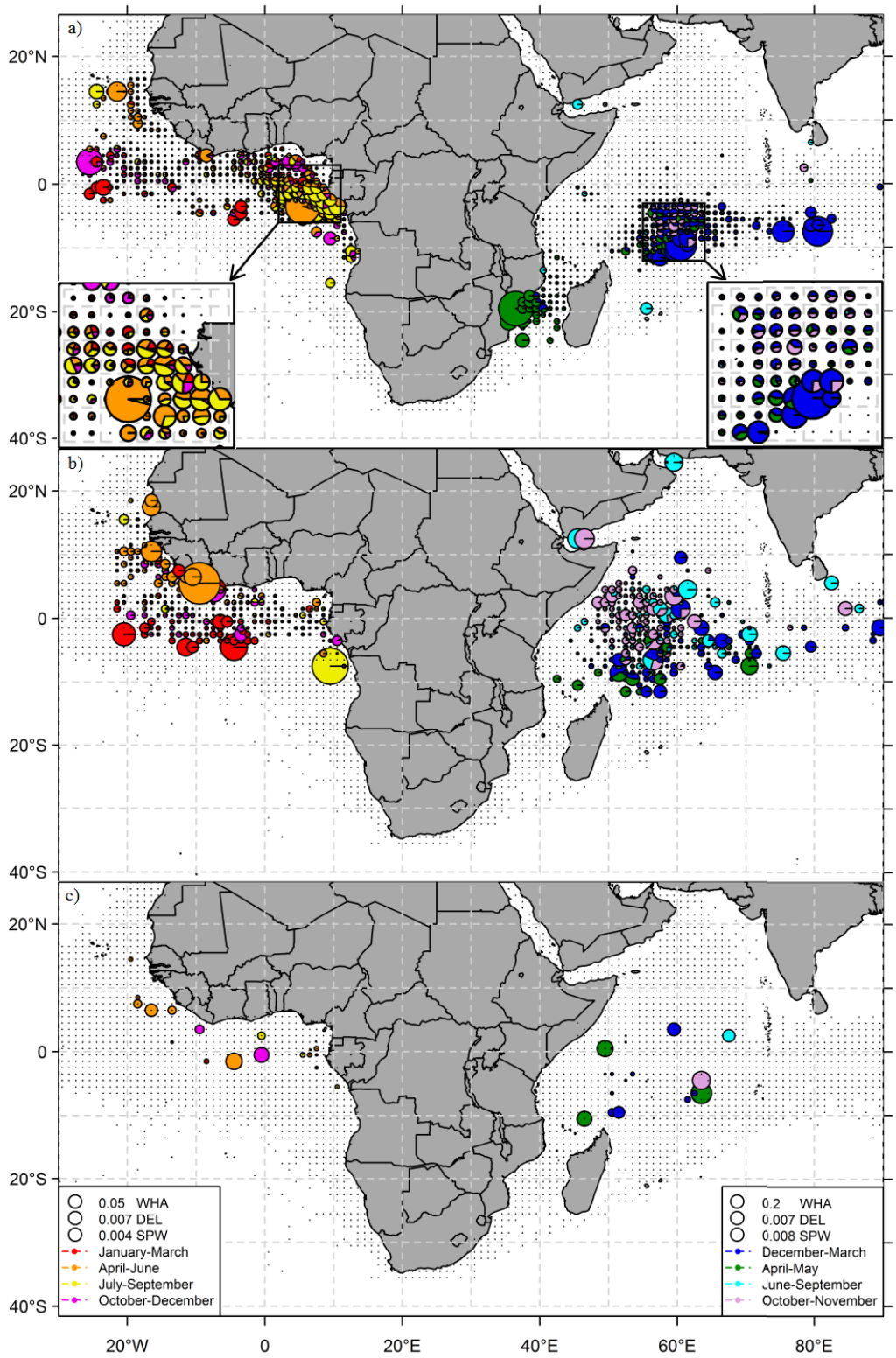

Figure 3.2 The seasonal distribution of sightings per unit of effort (number of cetacean sightings divided by the total number of purse-seiner activities per 1° square) from logbook data (1980–2011; French and Spanish tuna purse-seine fleets) of a) baleen whales (WHA), b) delphinids (DEL), and c) sperm whales (SPW), in the eastern tropical Atlantic and western tropical Indian Oceans.

Table 3.3 Main statistics of logbook and scientific observer datasets on the French and Spanish tuna purse-seine fleets in the eastern tropical Atlantic Ocean (EAO) and in the western tropical Indian Ocean (WIO). Data are presented for broad cetacean groups: baleen whales (WHA), delphinids (DEL), and sperm whales (SPW).

	Logbooks (1980–2011)			**Observers (1995–2011)**		
	EAO	**WIO**	**Total**	**EAO**	**WIO**	**Total**
Number of activities	468 181	393 404	861 585	169 546	114 581	284 127
Cetacean sightings events	7443	11 560	19 003	1932	1449	3381
WHA	6865	10 937	17 802	1,118	610	1728
DEL	561	604	1 165	734	784	1 518
SPW	18	20	38	80	55	135
% Cetacean sightings per activity	1.59	2.94	2.21	1.14	1.26	1.19
Number of fishing sets	238 172	249 100	487 272	9969	6129	16 096
% sets among activities	50.87	63.32	56.56	5.88	5.35	5.67
Cetacean sightings associated with sets	5794	9391	15 185	363	183	546
WHA	5623	9301	14 924	299	150	449
DEL	175	83	258	55	30	85
SPW	6	7	13	9	3	12
% Cetacean sightings associated with set	77.84	81.20	79.91	18.79	12.63	16.15
% sets with cetacean associated	2.43	3.77	3.11	3.64	2.99	3.39
Number of sets with cetaceans encircled				74	22	96
% sets with cetacean encircled				0.74	0.36	0.60
% sets with cetacean encircled by total number of sightings events				3.83	1.52	2.84
Number of cetaceans encircled				155	39	194
Number of cetaceans fate known				153	37	190
Number of cetaceans apparent survival				142	37	179
% Cetacean apparent survival				92.81	100.00	94.21

For both oceans, logbook records indicated areas and periods with high cetacean-fishery co-occurrence. Main areas with high SPUE were located in the WIO: i) east of the Seychelles (0°N–15°S, 55°E–65°E), especially baleen whales during the NE monsoon and 3.2 3.3.a). Two other areas with relatively high baleen whale SPUE were also identified: i) in the EAO, especially in the coastal waters of Gabon between April and September, and ii) in the eastern part of the studied area in the WIO (around 8°S and 80° 3.2 3.3.a) during the NE monsoon. In this latter area, relatively high SPUE resulted from a low number of cetacean sightings and a low number of vessel activities.

The observer dataset contained a total of 284 127 activities, of which 16 096 were 3.3). A total of 3381 cetacean sightings were recorded in this dataset, 3.3 3.4 3.4). As with the logbook data, cetacean sighting rates were relatively low in

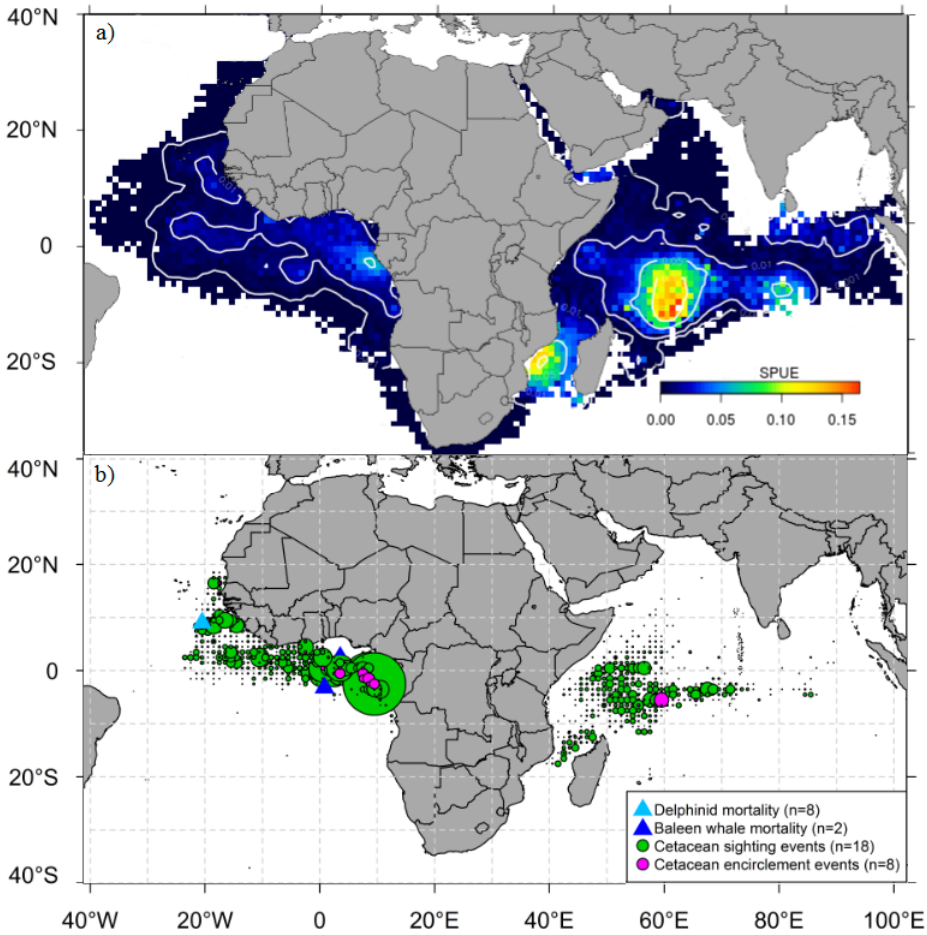

Figure 3.3 a) Distribution maps of calculated sightings per unit of effort (SPUE; number of cetacean sightings divided by the total number of purse-seiner activities, from the French and Spanish logbook data, 1980–2011) for all cetaceans groups combined, using a Poisson kriging method. b) Distribution of sightings, encirclements and mortalities of cetaceans (French and Spanish scientific observers' data, 1995–2011) per 1° square, in the Atlantic and Indian Oceans. The size of each symbol is proportional to the number in brackets (n); small dots also represent sightings ($n \geq 1$).

3.3).

Interactions between fishing operations and baleen whales were more commonly recorded than those involving delphinids (26% versus 5.6%). Within these set-associated sightings, over half of the interactions with baleen whales (52%) had been previously recorded as a sighting while the ship was searching for tunas, compared to only 14% for delphinids. Furthermore, the frequency of fishing sets being made following baleen whale sightings (within a radius of two miles) was 0.23, compared to 0.05 for delphinid sightings and 0.02 for sperm whale sightings.

Of all cetacean sightings recorded by observers in both oceans, only 546 (16%) were associated with sets. The percentage of fishing sets with cetaceans encircled was 3.3). Indeed 96 sets were recorded as

Table 3.4 Key statistics calculated using the scientific observer datasets of the French and Spanish tuna purse-seine fleets in the tropical eastern Atlantic (EAO) and western Indian Oceans (WIO) for baleen whales (WHA), delphinids (DEL), and sperm whales (SPW).

	Observers (1995–2011)	**EAO**	**WIO**	**Total**
Baleen whales (WHA)	WHA sightings events[1]	1118	610	1728
	% WHA sightings associated with set	26.7	24.6	26.0
	% sightings already recorded previous to the set	56.9	41.3	52.7
	Number of WHA encircled[2]	93	29	122
	Number of WHA fate known	92	27	119
	% WHA apparent survival	96.73	100.0	97.1
Delphinids (DEL)	DEL sightings events[1]	734	784	1,518
	% DEL sightings associated with set	7.5	3.9	5.6
	% sightings already recorded previous to the set	16.4	10.0	14.1
	Number of DEL encircled[2]	62	10	72
	Number of DEL fate known	61	10	63
	% DEL apparent survival	86.9[4]	100.0	87.5
Sperm whale (SPW)	SPW sightings events[1]	80	55	135
	% SPW sightings associated with set	11.3	5.5	8.9
	% sightings already recorded previous to the set	44.4	33.3	41.7
	Number of SPW encircled[3]	0	0	0

[1]Observation of a group of cetaceans, the number of individual could not be estimated
[2] Number of individuals encircled by the net
[3] Three humpback whale (*Megaptera novaeangliae*) mortalities (one in a fishing set in 1999 and two in a set in 2000)
[4] Eight pantropical spotted dolphin (*Stenella attenuata*) mortalities (in three different fishing sets in 1995)

having encircled cetaceans (194 individuals) which can be related to the possible intentional setting of nets in the vicinity of cetaceans: in 70% of encirclements, observers had already recorded the sightings during the previous activity (i.e. prior to the net being set). Only baleen whales (122) and delphinids (72) were recorded as encircled, and the majority of 3.3 3.4 3.3 3.4). Out of 155 individuals encircled in the EAO, three humpback whales in two separate sets and eight 3.3 3.4 3.3 3.4). In the WIO, 39 individuals were encircled but no mortalities were recorded. Thus, the apparent survival rates for cetaceans following encirclement were 93% (142 apparent survivals out of 153 known fates) in the EAO and 100% (37 apparent survivals 3.3).

3.4 Discussion

Areas of relatively high co-occurrence between cetaceans and the purse-seine fisheries of the EAO and WIO were identified for specific regions and periods. High baleen 3.2), as Robineau 1991 Romanov 2002), as well as in the Mozambique Channel during the ISW monsoon. In the EAO, significant baleen whale SPUEs were recorded in the coastal waters of Gabon between April and September. Whale-associated sets were reported earlier in Venezuelan purse-seine fisheries throughout the year in the Gaertner and Medina-Gaertner 1999).

Due to their size and high metabolic rates, baleen whales are assumed to require high Piatt and Methven 1992). Tuna purse-seine fishing grounds are commonly characterized by oceanographic conditions that attract prey species in high densities. Thus, the interaction between cetaceans and tuna fisheries may be driven by the distribution of Ballance and Pitman 1998 Mannocci *et al.* 2014). Areas where co-occurrence with purse-seine fisheries was most frequent are highly productive zones featuring upwelling, Hermes and Reason 2008), in the Hardman-Mountford *et al.* 2003), and Tew-Kai and Marsac 2009). While the observed overlap between regions of high productivity and areas of relatively high co-occurrence seems to support the assumption that cetaceans-fisheries interaction is mostly driven by prey abundance, cetacean distributions may also be influenced by reproductive behavior (i.e. suitable breeding or calving habitats). More studies are needed to identify the environmental conditions linked to the co-occurrence between cetaceans and purse-seine fisheries. Specific environmental variables (e.g. depth, distance to the shore, sea surface temperature, primary productivity, salinity, mixed layer depth, oxygen minimum zone depth, Ready *et al.* 2010 Forney *et al.* 2012 Sequeira *et al.* 2012)) and accurate statistical methods should be used to characterize factors which could explain the co-occurrence that is observed.

To improve their fishing success, fishers sometimes exploit the behavior of cetaceans Perrin *et al.* 1973 Clua and Grosvalet 2001 Romanov 2002 Amandè *et al.* 2010). In the logbook dataset, the majority of cetacean sightings were baleen whales, while in the observer dataset the number of baleen whale sightings was similar to 3.3). As the logbook sightings were mostly associated with fishing operations, the low record of delphinid sightings suggests that there is a low association

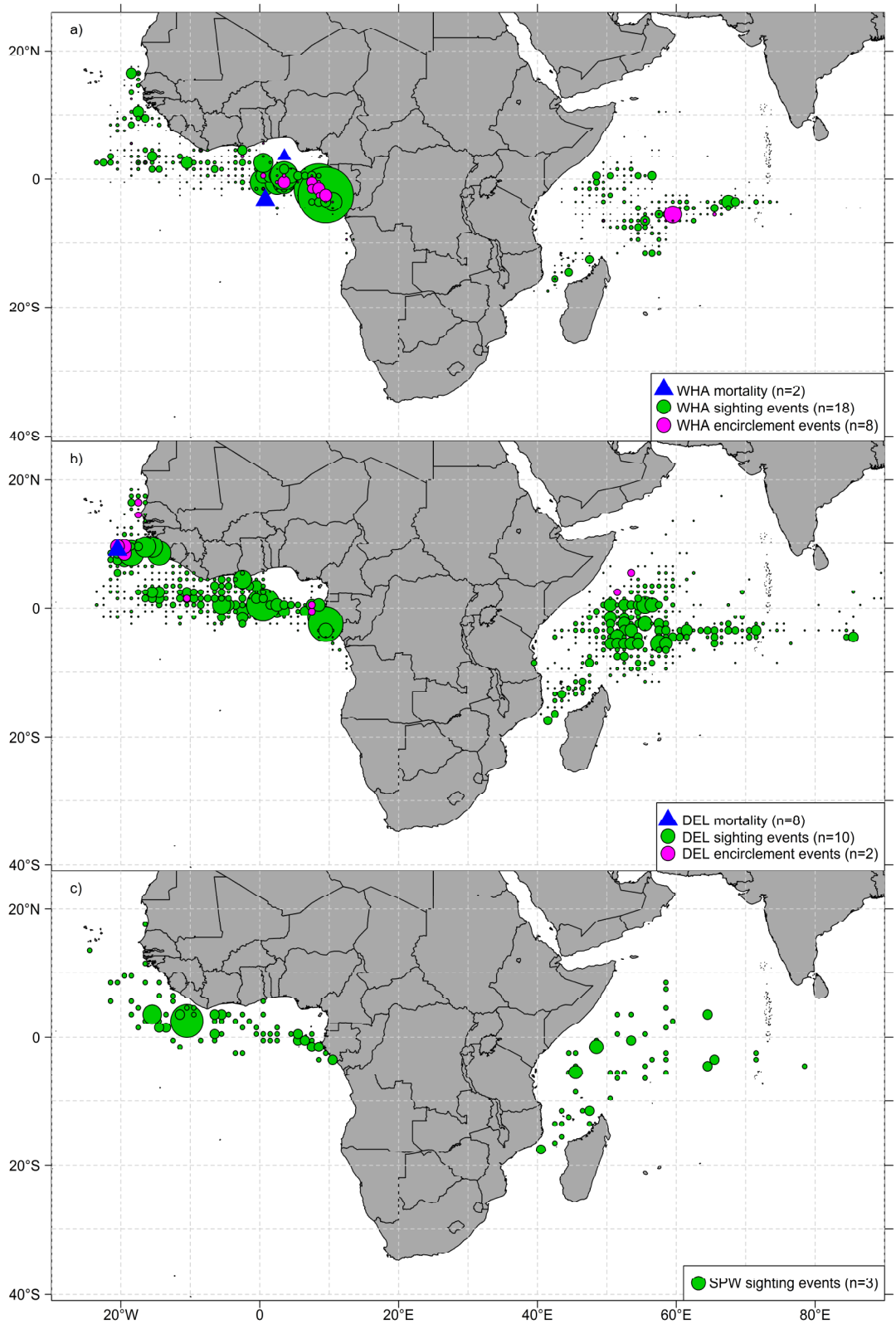

Figure 3.4 The distribution of sighting, encirclement, and mortality records from scientific observer data (1995–2011; French and Spanish tuna purse-seine fleets) of a) baleen whales (WHA), b) delphinids (DEL), and c) sperm whales (SPW) in the eastern tropical Atlantic and western Indian Oceans. Circle size is proportionzl to the number in brackets (n).

between delphinids and purse-seiners. Thus, captains may be less likely to record delphinid sightings as baleen whales are more often associated with tuna schools. In contrast, observers recorded sightings during all activities regardless of the cetacean group sighted, which could explain the difference in the proportion of sightings per group between the two datasets.

The majority of baleen whale sightings recorded by captains were associated with fishing sets and at least one in every two whale-associated sets was intentionally set in the vicinity of baleen whales. Conversely, while delphinids were recorded as frequently as baleen whales in the observer dataset, they were rarely recorded interacting with fishing sets, which supports the low association of delphinids to fishing sets. This suggests that once sighted, captains are likely to set a net close to, or around, baleen whales but not to delphinids. This assumption is further reinforced by the higher frequency of fishing sets being made following baleen whale sightings as compared to delphinid sightings. Given that baleen whales and delphinids (which can form large groups of several hundred individuals) have a similar level of detectability, these figures suggest that tuna purse-seiners may consider baleen whales as good indicators of the presence of tuna schools and often intentionally set whale-associated nets in the EAO and WIO.

In contrast, dolphin-associated sets appear to be made relatively rarely (< 10 per year) in the studied regions. This highlighted the striking difference between these tropical oceans and the EPO, where dolphin-associated sets are often made by captains (from 9000 to Hall and Roman 2013). It should be stressed, that similar dolphin species were observed between our study areas and the EPO, including pantropical spotted and Hall 1998 Gilman 2011) and that the same tuna species (i.e. large-size yellowfin tuna) are also present in all three ocean regions. The difference in the tuna-dolphin associations in the study areas and the EPO is likely due to environmental differences in the Scott *et al.* 2012). Indeed assumptions have been formulated to explain this difference, specifically because the EPO presents particular oceanographic features: a shallow thermocline, warm sea surface temperatures, and a thick oxygen minimum zone Edwards 1992 Fiedler and Talley 2006). These characteristics are thought to enhance the Edwards 1992 Scott *et al.* 2012). Even if some cases of tuna-dolphin association have also been Levenez *et al.* 1979 Ballance and Pitman 1998), using dolphins to detect tuna schools has not developed in the purse-seine fisheries in EAO and WIO. It is unclear whether this association is less Scott *et al.* 2012), or if captains are reluctant to set on dolphins due to the potential mortality and related consequences.

Sperm whale sightings have been recorded in both datasets; however, it is likely

Robineau 1991 Ballance and Pitman 1998 Weir 2011 Mannocci *et al.* 2014) rather than their possible interaction with either tuna schools or purse-seine fisheries. Indeed tuna and sperm whales are not considered to form mixed-species associations, as they do not share similar foraging Romanov 2002). Sperm whales mostly predate on large mesopelagic cephalopods Spitz *et al.* 2011), and tunas in surface aggregations predate mostly on epipelagic fish, Bashmakov *et al.* 1991 Potier *et al.* 2004).

Overall, the encirclement of cetaceans by purse-seine nets was relatively rare in the EAO and WIO. In most cases, data suggested that encirclement followed intentional cetacean-associated sets, but the data also indicated some accidental encirclements. When encircled, cetaceans usually escaped by either diving before the set was completed, swimming over Romanov 2002, personal communications from scientific observers and vessel captains). While baleen whales escaping may induce some damage to the net, it is minor compared to the resulting amount of tuna caught.

The apparent cetacean survival rates were relatively high. In the WIO, no mortalities were recorded in our study, although a single fatality of a young sei whale due to encirclement Romanov 2002) for the Soviet purse-seiners. Eleven incidental mortalities were recorded in the EAO (eight pantropical spotted dolphins and three humpback whales), representing an apparent survival rate of 92%. Although these figures are heartening, it is important to note that the non-lethal impacts of cetacean-associated sets have not been Wilson *et al.* 2014).

Since 2007, encircling cetaceans has been prohibited by the EU in both the EAO EU 2007). The IOTC introduced their own regulations for the Indian Ocean IOTC 2013; resolution 13/03), but the ICCAT has not yet introduced similar measures for the Atlantic Ocean. Given the lack of accurate cetacean-fisheries interaction data that existed for the tropical EAO and WIO, these measures were precautionary. Through a statistical analysis of two large datasets, we have shown that the magnitude of co-occurrence and interactions between cetaceans and purse-seine fisheries varies depending on factors such as the species involved, season, and area considered. Our results show that while intentional setting in the vicinity of baleen whales seems common, few interactions between fishing operations and delphinids were observed. In addition, we found a low apparent mortality during sets, which suggests that purse-seine fishing activities have a limited impact on cetaceans in the tropical EAO and WIO. The apparent survival rates determined here were based on the observer dataset which covered 7% – 9% of the European fleet activities during the studied period, and will be increased to 100% by 2014 (an increase to 50% has already occurred since July 2013). Overall, this research contributes

to the development of effective measures for the sustainable management of tropical tuna fisheries and the conservation of cetacean species.

Acknowledgements

We thank the editor P. Corkeron, L.T. Ballance and an anonymous reviewer for their constructive comments on a previous version of the manuscript. We are grateful to the fishing masters and scientific observers involved in the data collection, to the fishing companies, and to Terres Australes et Antarctiques Françaises (TAAF) for their close collaboration with European fisheries scientists (IRD/IEO/AZTI). The collection of logbook data is supported by the French and Spanish National Fisheries Administrations and the scientific observer programs are co-financed by the European Data Collection Framework (Regulation (CE) 199/2008) and various scientific institutions (IRD/IEO/AZTI). We thank P. Cauquil, C. Rodriguez (IRD), S. Rodriguez (IEO), and J. Ruiz (AZTI) for their valuable database support and P. Dewals (IRD) for conducting the interviews with vessel captains. We are also grateful to participants of the Sub-Committee on Ecosystems of the ICCAT and Working Party on the Ecosystems and Bycatch of the IOTC for their comments on the draft manuscript. Jane Alpine and Anne-Elise Nieblas have provided the English language editing for this paper.

In Chapter 3, it has been identified that baleen whales are directly interacting with the purse-seine fishery as most sightings recorded in both logbook and scientific observer databases were associated with fishing sets. In contrast, dolphins are in co-occurrence with the purse-seine fishery as they are present in fishing areas but do not interact with the fishery. In addition, it has been found that the majority of whale associated fishing sets were intentional (57%), with the baleen whale mostly sighted prior the setting of the net. It should also be mentioned that similar method to identify intentional or accidental setting of purse-seine nets around cetaceans has been performed for whale sharks (i.e., in case of whale shark set, checking if the whale shark sighting was also recorded during the activity just prior the set). It was found that 21% of the whale shark associated sets were intentional as the whale shark has not been recorded prior the setting of the purse-seine net. In addition to the identification of the context of cetaceans and whale sharks sightings, the spatio-temporal co-occurrence and interaction between these megafauna species and the tuna purse-seine fishery, as well as impacts of the fishery on the species, have been investigated. The purse fishery had limited apparent impact on cetaceans and whale sharks. However, unlike for whale sharks, baleen whales mostly escape by themselves before the closure of the net or by going through the net. Hence post-encirclement survival or non lethal impacts have not been investigated and methods to investigate it would be very difficult to implement. Finally, similar main areas and periods of co-occurrence between whale sharks, cetaceans and the purse-seine fishery have been found in both oceans. Complementarily, it is now relevant to investigate possible link between these main areas of co-occurrence and specific environmental conditions. The main areas and periods of co-occurrence identified correspond to productive environments (upwelling, river discharge or high eddy activity). This is logical as both baleen whales and whale shark are filter feeders. Therefore this may drive the distribution of these species through the distribution of prey species and indirectly be linked to the co-occurrence with the purse-seine fishery, which also occurs in productive oceanic areas. This will thus be investigated in the following chapter using proxy of productivity, as well as other environmental variables.

Chapter 4

Environmental factors and megafauna spatio-temporal co-occurence with tuna purse-seine fishery.

Environmental factors and megafauna spatio-temporal co-occurence with purse-seine fisheries.

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Published in Fisheries Oceanography (Article 4)

Escalle, L., Pennino, M. G., Gaertner, D., Chavance, P., Delgado De Molina, A., Demarcq, H., Romanov, E., Mérigot, B. (2016) Environmental factors and spatio-temporal interactions doi:

10.1111/fog.12163

Abstract

Tropical tuna purse-seine fisheries spatially co-occur with various megafauna species, such as whale sharks, dolphins and baleen whales in all oceans of the world. Here we analyzed a ten-year (2002–2011) dataset from logbooks of European tropical tuna purse-seine vessels operating in the tropical eastern Atlantic and western Indian Oceans, with the aim of identifying the principle environmental variables under which such co-occurrence appear. We applied a Delta-model approach using Generalized Additive Models (GAM) and Boosted Regression Trees (BRT) models, accounting for spatial autocorrelation using a contiguity matrix based on a residuals autocovariate (RAC) approach. The variables that contributed most in the models were chlorophyll-a concentration in the Atlantic Ocean, as well as depth and monsoon in the Indian Ocean. High co-occurrence between whale sharks, baleen whales and tuna purse-seine fisheries were mostly observed in productive areas during particular seasons. In light of the lack of a full coverage scientific observer on board program, the large, long-term dataset obtained from logbooks of tuna purse-seine vessels is highly important for identifying seasonal and spatial co-occurrence between the distribution of fisheries and megafauna, and the underlying environmental variables. This study can help to design conservation management measures for megafauna species within the framework of spatial fishery management strategies.

Key words

Cetaceans; GAM-BRT; marine conservation; purse-seine fishery; residual autocovariate; whale sharks; western Indian Ocean, eastern Atlantic Ocean.

4.1 Introduction

In the open ocean, the tropical tuna purse-seine fishery co-occurs with several megafauna species, including sharks and cetaceans, which are often emblematic species very vulnerable to natural and anthropogenic impacts. Some of these species, such as whale sharks (*Rhincodon typus*), baleen whales or dolphins, may serve as sighting cues by purse-seine fishermen for the presence of tuna schools at the surface of the sea and/or Romanov 2002 Capietto *et al.* 2014 Dagorn *et al.* 2013). Considering the decline of their populations and the multiple threats they have to face, whale sharks and all cetacean species which co-occur with purse-seine fisheries have been listed by the IUCN (www.redlist.org).

Rowat and Brooks 2012) and occurs across all warm temperate seas. Whale sharks spend most of their time near the surface to feed on pelagic invertebrates (e.g. krill, shrimp eggs, copepods) or small forage Rowat and Brooks 2012). While feeding near the surface, whale sharks typically swim Gaertner and Medina-Gaertner 1999). For this reason, whale sharks are considered as "living" FAD by fishers. In the eastern Atlantic (EAO) and the western Indian (WIO) Oceans, whale sharks co-occurrence with the purse-seine fishery is relatively low (1.5% of the total number of fishing sets are associated with whale sharks) and takes place in specific areas and periods: the waters off Gabon in the EAO from April to September and in the Mozambique Channel Sequeira *et al.* 2012 Capietto *et al.* 2014).

In the case of dolphins, schools of large yellowfin tuna (*Thunnus albacares*) are known to associate with the pantropical spotted dolphin (*Stenella attenuata*) and the spinner dolphin (*Stenella longirostris*) in the eastern tropical Pacific Ocean (EPO), probably to reduce Perrin 1968 Hall 1998 Scott *et al.* 2012). In this ocean, purse-seine vessels chased then encircled dolphin groups in order to catch associated tuna schools Hall 1998). While the tuna-dolphin association has been observed in the EAO and WIO Levenez *et al.* 1979 Ballance and Pitman 1998), few dolphin-associated sets have been Escalle *et al.* 2015). Indeed, in these oceans, most of the co-occurrence between purse-seine fishing operations and cetaceans (3% of all fishing sets) involved baleen whales (Bryde's whale *Balaenoptera edeni*, fin whale *Balaenoptera physalus*, sei whale *Balaenoptera borealis*, and humpback whales *Megaptera novaeangliae*) and occurred mostly east of the Seychelles from December to March and in the Mozambique Channel from December to Escalle *et al.* 2015). It is assumed that tunas and baleen whales may form foraging associations to feed on the same

Romanov 2002), such as small pelagic fishes.

At the ocean basin scale, various environmental variables such as water temperature, primary production, currents and eddies may directly influence the distribution of large marine species or indirectly affect them through influences on the distribution of their prey Ready *et al.* 2010 Forney *et al.* 2012 Sequeira *et al.* 2012 Monsarrat *et al.* 2015). For example, as filter feeders, whale sharks can be attracted to high productivity events which Heyman *et al.* 2001). Similarly, the large-scale spatial distribution of cetaceans is considered to be principally influenced by water temperature but also locally by the distribution of prey species (Piatt et al. 1989, Ballance & Pitman 1998, Mannocci et al. 2014). In particular, baleen whales are assumed to require Piatt and Methven 1992).

In the EAO and WIO the European tropical tuna purse-seine fleet covers large area of the pelagic ocean. Cetaceans and whale sharks sightings are reported in logbooks as potential sightings cues for tuna schools. Here a long-term dataset of logbooks was used to investigate the co-occurrence of whale sharks or cetaceans and fishing operation in relation to local environmental conditions. However, sightings are dependent on the intensity of the fishing effort, which itself undergoes seasonal variation across the fishing areas. For this reason, an ecological study of the distribution of these megafauna species is beyond the scope of this study. The aim of this work was to identify environmental variables that may be linked to the spatio-temporal co-occurrence between the tuna purse-seine fishery and whale shark or cetaceans across seasons in the tropical EAO and WIO. Deeper knowledge of the spatio-temporal patterns of fishery/megafauna co-occurrence could allow for further development of spatial fishery management strategies. Detailed maps could provide an essential tool for identifying areas where the co-occurrence is high and could contribute to the conservation management of these species within an EAF management.

4.2 Material and methods

4.2.1 Studied regions and seasons

The regions analyzed represent the main fishing grounds of European (French and Spanish) purse-seine vessels operating in the tropical EAO and the WIO (see Appendix 4.A, for map of seasonal variations in sighting effort). These regions are influenced by different factors. The EAO circulation is influenced by the Benguela and Canary Currents that generate seasonal upwellings along the coast from South Africa to Gabon between Hardman-Mountford *et al.* 2003) and from Mauritania to Senegal

Benazzouz *et al.* 2014). The Congo River also has a major influence on environmental conditions in the area throughout the year and especially during the wet season (April to September), with significant input of fresh water and dissolved Hardman-Mountford *et al.* 2003). In the WIO, water circulation is driven by monsoonal atmospheric circulation and reflects complex interactions of the seasonally alternating Somali Current with the south Equatorial Counter Schott *et al.* 2009). Several areas with specific circulation can be identified: (i) the northern part of the region where monsoon-generated seasonal Somalian-Arabian upwelling drastically affects productivity, (ii) the Seychelles-Chagos thermocline ridge (55°E–65°E; 5°S–12°S) features a productive open-ocean upwelling Hermes and Reason 2008), and (iii) the Mozambique Schott *et al.* 2009).

In this context of high difference in hydro-climatic conditions between both oceans, the year was divided into four seasons for each ocean differently. In the EAO, the seasons were defined as four quarters starting in January (labeled 1 to 4). In the WIO, the seasons reflected monsoon [north-east (NE) from December to March and south-west (SW) from June to September] and inter-monsoon [south-west (ISW) in April–May and north-east (INE) in Capietto *et al.* 2014 Escalle *et al.* 2015).

4.2.2 Fishery logbooks

The sightings and effort data were obtained from logbook records from all European tropical tuna purse-seine vessels. In both oceans the activities of the fleets have been monitored by the IRD and the IEO, for French and Spanish vessels, respectively (average of 35 and 59 vessels per year over the 2002–2011 period).

We considered a ten-year time series (2002–2011) of purse-seine activities, to match the available environmental dataset (see below). An "activity" was defined as a record reported by vessel captains, which is (i) made for each fishing set, or (ii) in cases when no fishing set occurred during one day the main activity of the day (e.g. search for tuna or transit between fishing areas) is recorded with geographic position at noon (∼1.2–2.2 ° [1]). In this way, most of the activities are fishing sets and more than one activity per day can be recorded. Each record of activity included time, geographic position (only at the beginning of a fishing set), information on associations

[1]Approximate maximum distance when considering a purse-seiners cruising (transiting or searching for tuna school) speed of 10–13 knots (18–24 km/h), a crew watch of ∼10 hours a day (daylight), and 1° at the equator (111 km).

between tuna schools and baleen whales, dolphins, whale sharks, flock of birds, or floating objects (natural log or FAD). For each fishing set estimated weight and catch composition of targeted tuna species were also reported. Whale shark or cetacean (baleen whales or dolphins) sightings (up to 5 nautical miles) are defined as the presence of individuals (the number of individuals was not recorded) during any vessel activity (i.e. fishing set, search for tuna or transit). Separate models for dolphins could not be fit considering the low number of sightings (59 and 89). Here we thus define megafauna and purse-seine fishery co-occurrence as any sighting recorded in logbooks, as we assumed that captains mainly recorded sightings indicating the presence of tuna schools or made during a fishing set. On the other hand, we define an association as the assemblage of a tuna school with a megafauna species (a group or one individual) that can be formed for ecological consideration (e.g. foraging associations). Activity and sighting data were then aggregated into 1° squares (∼12,300 km2 at the equator) in R 3.0.2. (R Development Core Team 2014).

4.2.3 Environmental variables

With the aim of characterizing (1) the epipelagic environment, and tentatively (2) the distribution of whale sharks and cetaceans' main prey (macroplankton, micronekton, fish), two physical variables: Sea Surface Temperature (SST) and Eddy Kinetic Energy (EKE), one biological variable: chlorophyll-a concentration (CHL), and three bathymetric variables: 4.1).

[2] [3]

[4] (1997–2007) for CHL), only a single sensor time series was selected for each variable to avoid instrument-specific biases in the data, in our case MODIS for both SST and CHL. The appropriate environmental dataset was selected for each variable to cover the largest period of time possible and to provide appropriate spatial resolution (at least 1° 4.1). All environmental data were aggregated (i.e. averaged) at a 1° x 1° resolution to reduce missing values induced by cloud cover and to provide the equivalent spatial resolution to that of the fishery activity data.

In addition to environmental variables, a seasonal effect was introduced in the models (see below) as a categorical variable, to account for the spatio-temporal co-occurrence between fisheries and species. Seasons are known to highly influence the spatial distribution Robineau 1991 Sequeira *et al.* 2012 Capietto *et al.* 2014 Escalle *et al.* 2015) and a preliminary analysis (Kruskal-Wallis tests) revealed a non-random

[2]MODIS - Moderate Resolution Imaging Spectroradiometer (http://oceancolor.gsfc.nasa.gov)
[3]AVHRR - Advanced Very High Resolution Radiometer (http://www.nodc.noaa.gov/sog/pathfinder4km/)
[4]SeaWIFS - Sea-viewing Wide Field-of-view Sensor (http://oceancolor.gsfc.nasa.gov/)

Table 4.1 Predictor variables used for modelling whale sharks and cetacean co-occurrence with purse-seine fisheries in the Atlantic and Indian Oceans.

Variables	Abbreviation	Resolution		Sensor	Information
		Spatial	Temporal		
Sea Surface Temperature (° C)	SST	4 km	8 days	MODIS-Aqua	SST and CHL were extracted from satellite data, covering the period 2002–2011.
Chlorophyll-a concentration ($mg.m^{-3}$)	CHL	4 km	8 days	MODIS-Aqua	
Eddy Kinetic Energy ($m^2.s^{-2}$)	EKE	0.33°	7 days	w-aviso 3 (MSLA[a])	EKE corresponds to the Sea Level Anomaly intensity, for the 2002–2011 period. $EKE = 1/2(U^2 + V^2)$
Distance to land (km)	LandDist	0.5°	-	AquaMaps dataset Kaschner *et al.* 2008)	Distance to the nearest shoreline.
Depth (m)	Depth	0.02°	-	NOAA-NGDC ETOPO1 Global Relief Model Amante and Eakins 2009)	Extracted from this 1 arc-minute global relief model of Earth's surface, which integrates land topography and ocean bathymetry, for each exact location of an activity.
Slope (%)	Slope	-	-		Calculated from the depth with the slope Hij- mans *et al.* 2014) in R 3.0.2.

[a] Maps of Sea Level Anomalies & geostrophic velocity anomalies http://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/global/msla.html

distribution of whale shark and cetacean sightings between the different seasons. Activities, sightings and environmental variables were thus averaged per 1° square and season (quarters or monsoon periods, over the whole 2002–2011 period). While an exploratory analysis also found annual variability in the time-series, our interest was to describe average trends in oceanographic features and produce seasonally predictive maps. Therefore, we focused our analysis on the seasonal effect, which also increased computational efficiency. Thus, the candidate explanatory variables were SST, EKE, CHL, Depth, Slope, LandDist and Seasons, and the response variable was the presence/absence per 1° square for the binomial model and the number of sightings per 1° square for the count model (see next section). Correlation between explanatory environmental variables was assessed using a draftsman's plot and the r Pearson correlation index. Variables were not highly correlated ($r < 0.6$), and were thus all considered in further analyses.

4.2.4 Model approach

In both oceans, our study aimed to develop two separate models of the count of whale sharks or cetaceans co-occurrence with the purse-seine fishery in relation to environmental variables and seasons. Whale shark and cetacean sightings are rare events compared to the 4.2). As a consequence, exploratory analysis highlighted some specific features inherent in the dataset which, together, directed our modelling strategy: (i) a large proportion of zeros, (ii) a non-linear relationship between the

response variable and explanatory variables, (iii) spatial autocorrelation and (iv) high variability in the intensity of fishing effort with areas and seasons. Various statistical approaches

Liu *et al.* 2011

Lin and Zhang 1999 for Generalized Additive Mixed Model (GAMM)), but none can do so simultaneously and/or provided poor accuracy when applied to our dataset.

Lo *et al.* 1992) to deal with high numbers of zero sightings, which includes two stages: (i) modelling presence/absence in order to obtain the envelope of the predicted probability of presence of the species studied

Monsarrat *et al.* 2015) as an example) and (ii) modelling the number of sightings (i.e. count data) of the studied species by the purse-seine fishery, only in areas where species were predicted to be present. For both stages, the candidate explanatory variables included all environmental variables, the season, and all possible interaction terms.

Table 4.2 Main statistics of French and Spanish logbook datasets used in the binomial and count models of whale sharks and cetaceans (baleen whales and dolphins) in the Atlantic and Indian Oceans.

	Atlantic Ocean	**Indian Ocean**
2002–2011 Period		
Number of fishing activities[1]	116 386	159 091
(fishing sets and search/transit)	(60 520 and 55 866)	(92 272 and 66 819)
Number of whale shark sightings	674	455
Number of cetacean sightings	1128 (1067 and 61)[4]	1275 (1183 and 92)[4]
Binomial model		
Number of fishing activities[1, 2]	112 867	158 828
Number of whale shark sightings	674	454
Number of grids with whale sharks present[3]	163	146
Number of cetacean sightings	1113 (1056 and 57)[4]	1275 (1183 and 92)[4]
Number of grids with cetaceans present[3]	347 (322 and 39)[4]	427 (397 and 81)[4]
Whale shark count model		
Number of fishing activities[1]	57 689	124 443
Number of whale shark sightings	611	440
Cetacean count model		
Number of fishing activities[1]	96 442	129 205
Number of cetacean sightings	1113 (1056 and 57)[4]	1196 (1122 and 74)[4]

[1] Activities include all fishing sets, as well as the search for tuna school or transit between fishing areas.
[2] Reduced dataset following the removal of missing values in environmental data due to cloud coverage, implemented in the models.
[3] One or more sightings per 1°x1° grid cell.
[4] The numbers in brackets are the details for baleen whales and dolphins, respectively.

To deal with non linear and non-monotonic relationships between response and explanatory variables, we used two statistical methods in both previous steps: Generalized Hastie and Tibshirani 1986 Elith *et al.* 2008). GAMs have previously been used on complex species distribution patterns Guisan *et al.* 2002 Afonso *et al.* 2014 Mannocci *et al.* 2014 Wood 2013). In GAM models, we used the default Wood 2003), "ti" parameter was used for interactions terms, and we limited the smoothing to 4 degrees of freedom for each spline to avoid overfitting. BRT combines regression trees and boosting methods to fit complex nonlinear relationships between predictors and the response variable, automatically Elith *et al.* 2008). The "train" function from the Kuhn 2008) uses a resampling method to evaluate the effect of model tuning parameters on performance, and to select the "optimal" model. To keep the model simpler and easier to interpret, we chose to build the model with a tree complexity of 2 and a learning rate of 0.01; the optimal number of boosting trees was assessed with the "gbm.step" Hijmans *et al.* 2014). In order to compare with the GAM, results from BRT were expressed in percent (using the total percentage of deviance explained by the model) as the relative influence of each variable to the model.

To account for the spatial autocorrelation in the data we implemented the residuals Crase *et al.* 2012) during both stages of the Delta-model, for both GAM and BRT. Here the spatial autocorrelation was included by adding another term to the model (the autocovariate), which represents the influence of neighbor observations on the response variable at a particular location (1° square). For each model, the RAC approach was implemented as follows: first, the model (GAM or BRT in our case) was computed with a variable backward stepwise selection procedure based on the information theory criteria ("AIC") and this procedure and the principle of parsimony were used to determined the number of interaction terms. Secondly, residuals from the selected model were calculated for each grid cell and were used to compute the autocovariate by a focal calculation. This allowed cells from a selected neighbor to have a weight of 1 and all other cells a weight of 0. Finally, the residuals autocovariate was considered as an explanatory variable in the previous Crase *et al.* 2012). Spatial autocorrelation was tested for each model by calculation Bivan 2010), which indicates correlation between observations depending on the distance between them.

The GAM and BRT binomial RAC models based on the presence/absence of whale sharks and cetaceans were performed separately for each ocean. A binomial distribution (logit function) was applied to deal with binary data and to eliminate the possibility of

Zuur 2009). Effort (number of activities) couldot be accounted for in the binomial models, but only in the models of count data (see below), because its addition in the form of an offset term was not appropriate, and including it in the weight term strongly decreased the model performance and prediction. Validation of the binomial models was conducted through an internal 4-fold cross validation in which the relationship between occurrence data and the environmental variables was modelled using a training dataset (created by a random selection of 75% of the data) and the quality of predictions was then assessed using a validation dataset (created by a random selection of 25% of Fielding and Bell 1997). This calibration-validation procedure was repeated five times for each method, and averaged the resulting measures of model performance. During the model validation process, a confusion matrix that records the number of true/false positive/negative cases predicted by the model, was generated. From this matrix all the performance statistics were derived (e.g. area under the curve, specificity Fielding and Bell 1997 Pearce and Ferrier 2000), see Appendices 4.B to 4.E for definition and value derived from the models). Model validation was performed using the Freeman 2012). With the aim of calculating the envelope of presence of whale shark or cetaceans, the conversion of the predicted probability of presence into a binary presence/absence response was done for value above a threshold derived from the cross validation (see Appendices 4.B to 4.E).

Once the envelope of presence was obtained, different distributions were tested to model the number of sightings in areas where the species/group was predicted to be present (negative-binomial, quasi poisson and poisson). To account for the non-constant sighting effort between 1° square, the number of vessel activities was implemented as an offset in the Kotze *et al.* 2012). For whale shark and cetaceans, separately, the best model between classical GAM and BRT, and GAM and BRT RAC models was then selected based on the above mentioned prediction performance of binomial models, as well as residuals analysis, a plot of predicted versus observed values, and deviance explained for both binomial and count models (see Appendices 4.B to 4.E). The quasi-poisson GAM and the poisson BRT were the distributions that provided the most accurate results for our datasets. Note that an Araújo and New 2007), based on the combined predictions of the GAM and BRT, was also tested. However, in each case only one model (i.e. GAM or BRT) provided the best performances, while averaging the GAM and BRT predictions weakened them. For this reason the averaging approach was not adopted. Predictions by ocean per season from GAM and BRT models were projected onto a 1° x 1° grid, limited to areas with reported fishing activities by the European purse-seine fleet.

4.3 Results

Between 2002 and 2011, totals of 112 867 and 158 8281 fishery activities (110 452 [5] 4.2 for original statistics of logbook data), and over 1093 and 1,194 1° square grid cells were sampled. From this selected datasets, 674 and 454 whale shark sightings; and 1113 and 1275 4.2). For whale sharks, the best binomial models were BRT RAC in the EAO with all explanatory variables retained, and GAM RAC in the WIO with only Depth, EKE, CHL, Season and the interaction 4.3, Appendices 4.B and 4.C). For cetaceans, the best binomial models were GAM RAC in the EAO, with all explanatory variables significant, and BRT RAC in the WIO with all explanatory variables and the interaction between Depth and Slope 4.3, Appendices 4.D and 4.E).

For whale shark and for cetaceans, the best model to fit the number of sightings data was the BRT poisson RAC model (see Appendices 4.B to 4.E for details). The percentage

4.3, Appendices 4.B to 4.E) when season and environmental variables were considered (68.2–83.0% when the deviance from the autocovariate term is also considered). The Pearson

4.3, Appendices 4.B to 4.E). Absence (whale shark in the EAO and cetaceans in the WIO) or weak (for whale shark in the WIO and cetaceans in the EAO; p-value <0.05 but Moran's index of autocorrelation <0.02; see Appendices 4.C and 4.D) spatial autocorrelation was detected, highlighting that it was accurately handled by the RAC method.

For whale sharks in the EAO, the model explained 23.3% of the total deviance (83.0% with the autocovariate term) and the most significant variables were CHL, LandDist and 4.3). In the WIO, 9.9% of deviance was explained by environmental and season variables (70.1% with the autocovaritae 4.3), with the most significant variables being Season, Depth, EKE and SST 4.3).

For cetaceans in the EAO the total deviance explained was 21.5% (a total of 72.1% with the autocovariate term). SST (7.6%), CHL (6.6%), Slope (3.7%) and Depth (1.9%) were 4.3). In the WIO 32.5% of the deviance of the model was explained by season and environmental variables (68.2% due to the autocovariate term). In this model, depth accounted for the vast majority of the relative influence of each variable

[5] After the removal of 3.02% and 0.17% of activities as a result of missing values in the environmental dataset due to the cloud cover.

Table 4.3 Binomial and count models used for whale sharks and cetaceans in the Atlantic (EAO) and Indian Oceans (WIO). Numbers in brackets indicate the relative contribution of each explanatory variable (for BRT only). % De = total percentage of the deviance explained by each model (in brackets are the percentages of deviance explained by environmental and season variables); R2 = pseudo coefficient of determination; r = Pearson correlation index between observed and predicted values; I = Moran's index maximum absolute value for each model and associated p-value.

	Explanatory variables	% De	R^2	Pearson r	Moran's I	Moran p-value
Whale shark EAO						
BRT binomial RAC	CHL (5.4), SST (4.4), LandDist (2.4), Depth (1.6), EKE (1.4), Season (1.0), Slope (0.2), Autocovariate (19.0)	35.5 (16.5)		0.51	0.06	$< 2.2e^{-16}$
BRT poisson RAC	CHL (5.5), LandDist (5.1), Slope (5.1), SST (3.5), Depth (3.5), Season (0.4), EKE (0.1), Autocovariate (59.7)	83.0 (23.3)		0.94	0.02	0.06
Whale shark WIO						
GAM binomial RAC	Depth, EKE, CHL, Season, Autocovariate, ti(CHL, EKE)	12.3	0.06	0.26	0.12	$< 2.2e^{-16}$
BRT poisson RAC	Season (3.2), Depth (3.0), EKE (2.0), SST (1.1), CHL (0.5), Slope (0.1), Autocovariate (60.2)	70.1 (9.9)		0.54	0.03	0.10e-02
Cetacean EAO						
GAM binomial RAC	Depth, SST, CHL, EKE, Slope, LandDist, Season, Autocovariate, ti(Depth, Slope)	21.1	0.16	0.41	0.15	$1.2e^{-10}$
BRT poisson RAC	SST (7.6), CHL (6.6), Slope (3.7), Depth(1.9), Season (0.6), EKE (0.6), LandDist (0.5), Autocovariate (50.6)	72.1 (21.5)		0.92	0.02	$0.10e^{-02}$
Cetacean WIO						
BRT binomial RAC	CHL (5.5), SST (3.2), EKE (2.1), LandDist (3.8), Depth (1.8), Slope (0.5), Season (0.2), Autocovariate (15.0)	30.2 (15.2)		0.53	0.15	$2.0e^{-16}$
BRT poisson RAC	Depth (21.2), Season (4.3), Slope (3.0), SST (3.0), CHL (0.8), EKE (0.5), LandDist (0.3), Autocovariate (35.7)	68.2 (32.5)		0.77	0.04	0.28

(21.2%), nonetheless, season (4.3%), slope (3.1%) and SST (3.0%) still represented significant influence in the model.

Results showed several hotspots of whale shark and purse-seine fishery co-occurrence 4.1 4.2): (i) in the EAO, in the eastern part of the Gulf of Guinea, especially along the coast from Gabon to Angola during July–September, (ii) in the WIO, around the Seychelles during the NE monsoon, (iii) in the Mozambique Channel during ISW monsoon, and (iv) in the area north of the Seychelles and off Somalia EEZ (around 5°N–55°E) during the SW monsoon period.

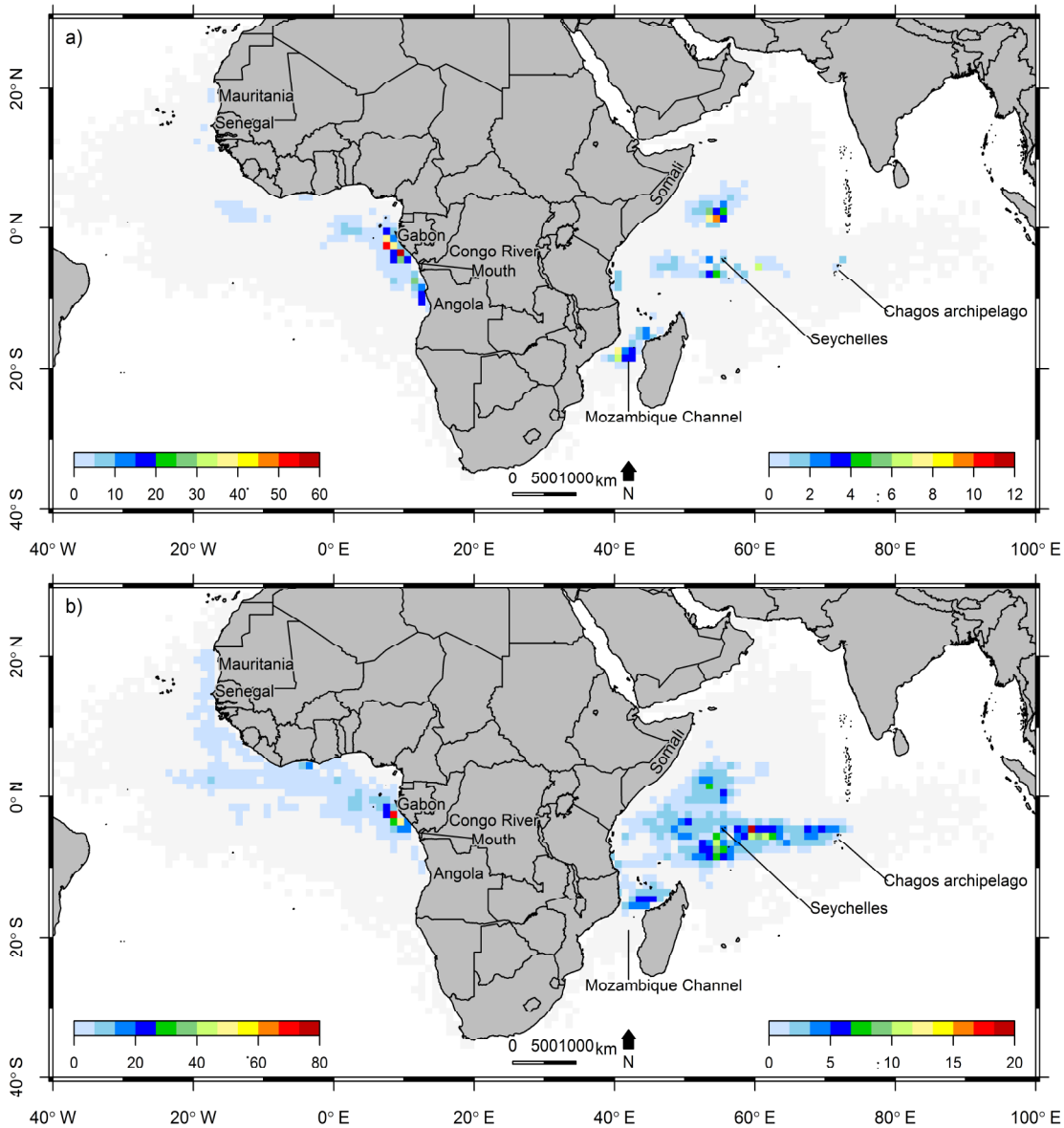


Figure 4.1 Prediction of co-occurrence between a) whale sharks and b) cetaceans and purse-seine fisheries in the tropical eastern Atlantic and western Indian Oceans derived from BRT poisson RAC models. Maximum values of a) 60 and 12 whale sharks, and b) 80 and 20 cetaceans, co-occurrence with the purse-seine fishery per 1° square, in the Atlantic and Indian Oceans, respectively.

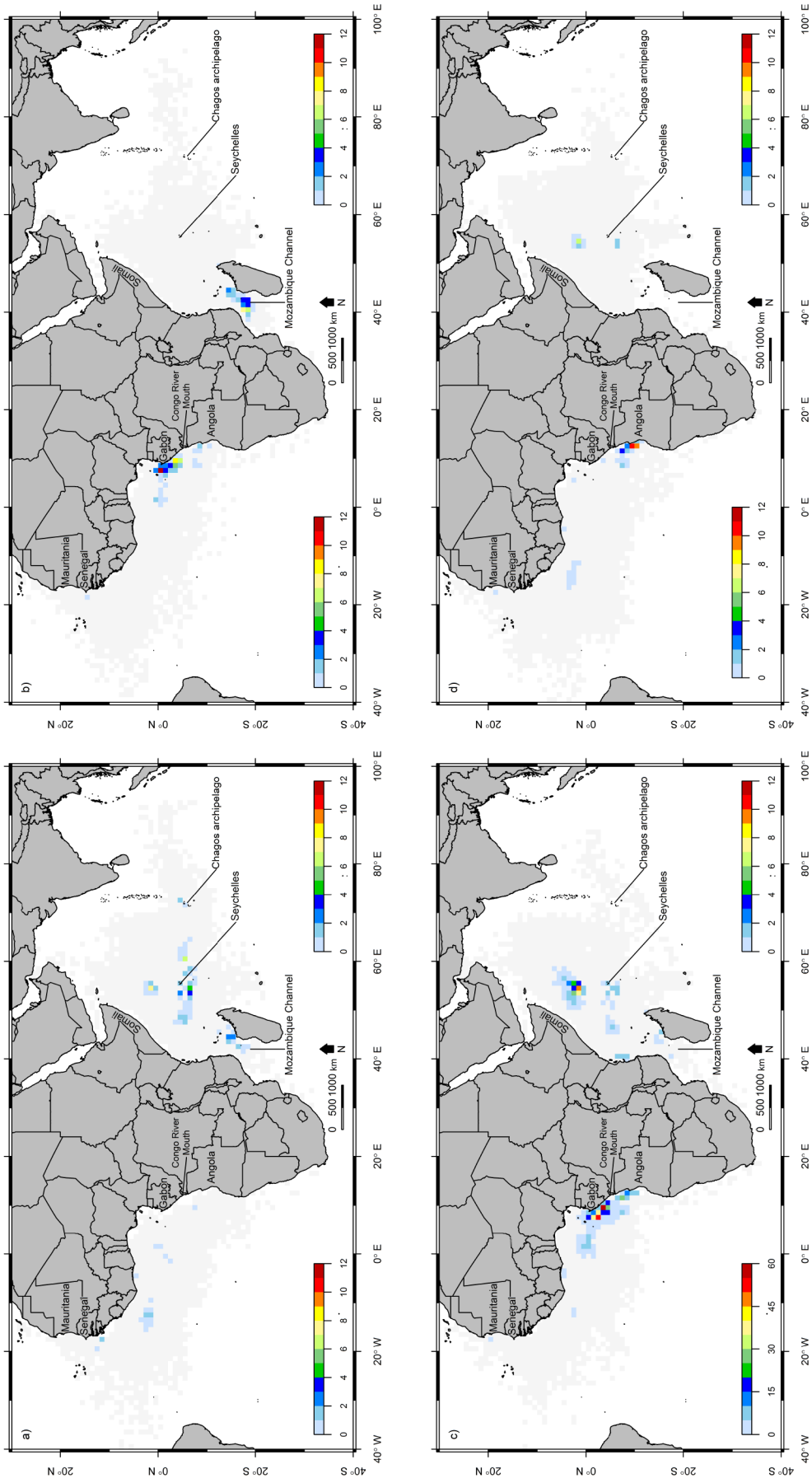


Figure 4.2 Seasonal distribution of the predicted co-occurrence between whale sharks and purse-seine fisheries in the tropical eastern Atlantic and western Indian Oceans,derived from BRT poisson RAC models. a) season 1 (Atlantic Ocean) and NE monsoon (Indian Ocean), b) season 2 and ISW monsoon, c) season 3 and SW monsoon, and d) season 4 and INE monsoon. Maximum values for the legend scale vary depending on the ocean and the season (12, 75 or 20 whale sharks /purse-seine fisheries co-occurrence per 1° square).

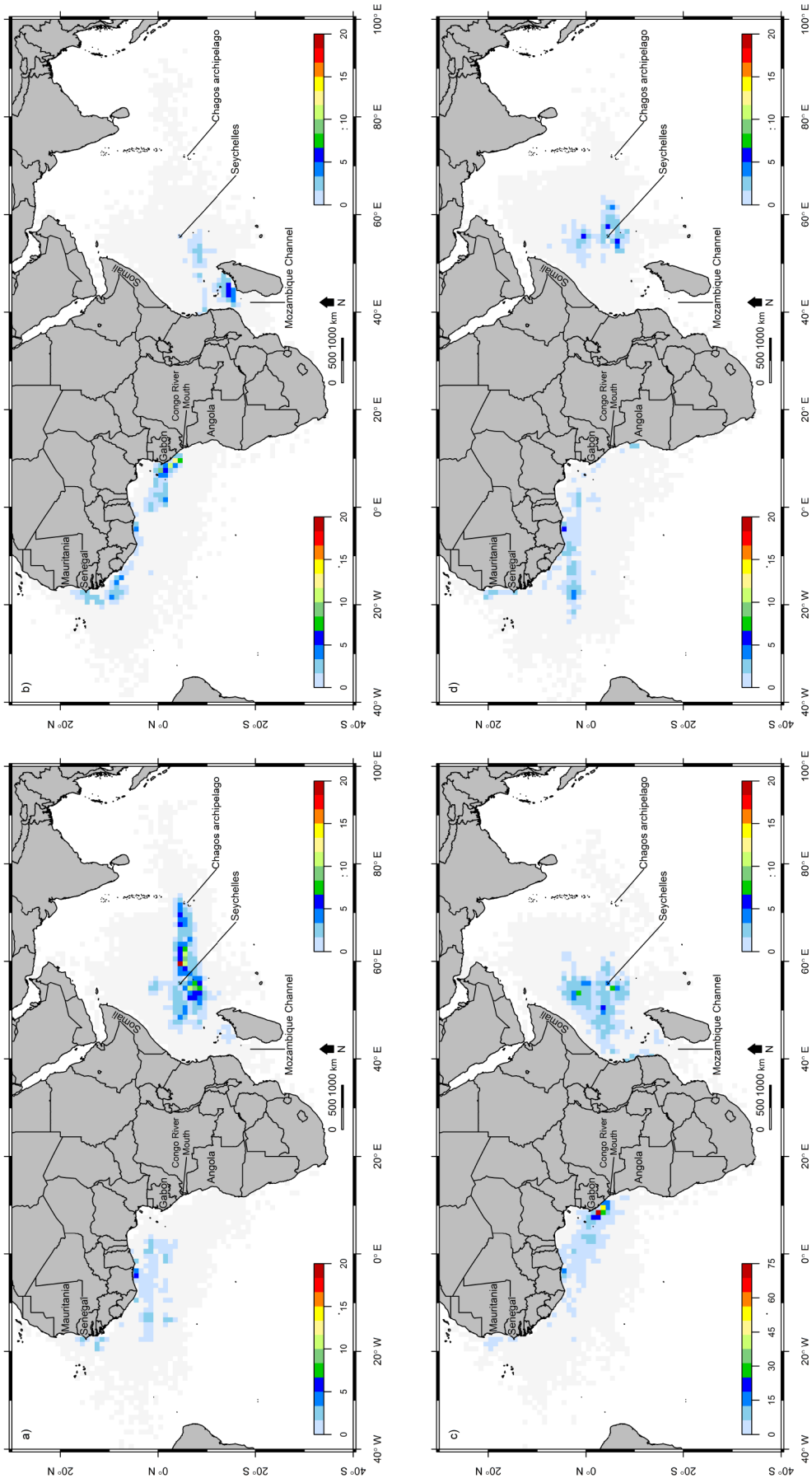


Figure 4.3 Seasonal distribution of the predicted co-occurrence between cetaceans and purse-seine fisheries in the tropical eastern Atlantic and western Indian Oceans, derived from BRT poisson RAC models. a) season 1 (Atlantic Ocean) and NE monsoon (Indian Ocean), b) season 2 and ISW monsoon, c) season 3 and SW monsoon (maximum value of 60 cetaceans /purse-seine fisheries co-occurrence per 1° square in the Atlantic Ocean), and d) season 4 and INE monsoon.

For cetaceans, the predicted number of sightings showed wider dispersal, especially 4.1.b), and high variations following seasonal and monsoonal patterns 4.3). In the EAO, cetacean/fishery co-occurrence varied from (i) the north of the Gulf of Guinea, above the equator, from 20°W to 5°E during season 1 and 4, (ii) north-east of the Gulf of Guinea, especially in the waters off Gabon during season 4.3). In the WIO, prediction of cetacean sightings by the purse-seine fishery ranged from (i) around the Seychelles (10°S–0°N and 50°E–75°E) during the NE monsoon, (ii) the north of the Mozambique Channel during the ISW monsoon, (iii) an area around and to the north of the Seychelles (10°S–8°N and 40°E–65°
4.3).

4.4 Discussion

Using a long-term tropical tuna purse-seine logbook dataset, we investigated links between the co-occurrence of purse-seine fisheries with whale sharks and with cetaceans in relation to environmental variables in the tropical EAO and WIO. By implementing quantitative models which included environmental variables, our study is complementary to previous works that roughly identified spatio-temporal variations of co-occurrence of Capietto *et al.* 2014 Escalle *et al.* 2015). By incorporating a spatial correlation contiguity matrix as an explanatory variable in GAM and in BRT using the residuals autocovariate approach, we accounted for the autocorrelated nature of the Crase *et al.* 2012), showed good predictive results for both megafauna groups studied. In particular, it allows the spatial correlation, present in our dataset, to be dealt with and can be applied to rare species from fisheries dependent data (i.e. containing large proportions of zeros with varying intensity in observational effort), which cover large spatial scales. It should be stressed that the relatively low contribution of each environmental explanatory variables to the total deviance of the model (<1% to 21.2%) is similar or higher than those reported in other modelling studies Forney *et al.* 2012 Mannocci *et al.* 2014 for Afonso *et al.* 2014 for whale sharks). It should be mentioned that the logbook dataset used here contains inherent limitations, such as under-reporting or missed sightings by captains (e.g. when megafauna species are not associated with a tuna school). While captains recorded sightings of either baleen whales or dolphins, we used in the same model a broad group of cetacean species (both baleen whales and dolphins, which was not further discussed due to the low number of dolphin sightings), each with a different ecology and

biology. Furthermore, scientific observer data were not used in complement to logbook data as (i) many sightings would have been counted twice, (ii) it was not considered appropriate to have data from two different sources covering the same fishing trips (i.e. when observers are onboard, captains still fill logbooks), (iii) scientific observers data have relatively low and irregular coverage rate (in time and space). In addition, while in the EPO it has been shown that the tuna-dolphin association is promoted by shallow mixed layer and hypoxic Scott *et al.* 2012), these variables were not included here as the tuna-dolphin association is less encountered.

4.4.1 Whale sharks

Chlorophyll-a concentration explained a relevant portion of the deviance of the whale shark model in the EAO. Areas with high whale shark and fishery co-occurrence (i.e. the 4.1 4.2) matched areas with high chlorophyll-a [6] 4.4.a, Appendix 4.F), especially from April to September. This might reflect a larger regional phenomenon occurring in the Gulf of Guinea during this period linked to the principle rainy season in this area. A major discharge of fresh water, dissolved organic matter and floating objects from rivers into the oceanic system (specifically the Congo River) occurs during this period and peaks from April to June, with the emergence of a coastal Van Bennekom and Berger 1984). Such a productive area may explain the presence of whale sharks and tunas, by supporting high densities of prey. In the WIO, an opposite result was obtained. The concentration of chlorophyll-a was not a significant 4.3). One explanation for this result could be that, in this ocean, values of chlorophyll-a concentration are lower than in the EAO (average of 0.5 ±1.4 and 0.2 ±0.4 mg.m-3 in the EAO and WIO, respectively; Appendix 4.F). This might be due to very high concentrations of chlorophyll-a recorded in the EAO in areas influenced by the Congo River discharge. While seasonal peaks in productivity in the WIO, such as in the McCreary *et al.* 2013), they do not feature in our model, as few sightings were recorded directly in this area. However, in the WIO two small regions showing high whale sharks and fishery co-occurrence were also in very productive waters, due to the development of a seasonal Hermes and Reason 2008), and (ii) on the periphery of the Somalian-Arabian upwelling during the NE monsoon. Thus, it can be concluded that in both oceans, whale sharks occurred in highly

[6] Very high chlorophyll-a concentration is also detected year-round in the latitudinal band from 24 to 27°S 4.4.a). This represents the Benguela Current area, with high primary production, but very low overlap with purse-seine fishing activities.

productive environments. Such spatial co-occurrence was expected considering that the Rowat and Brooks 2012).

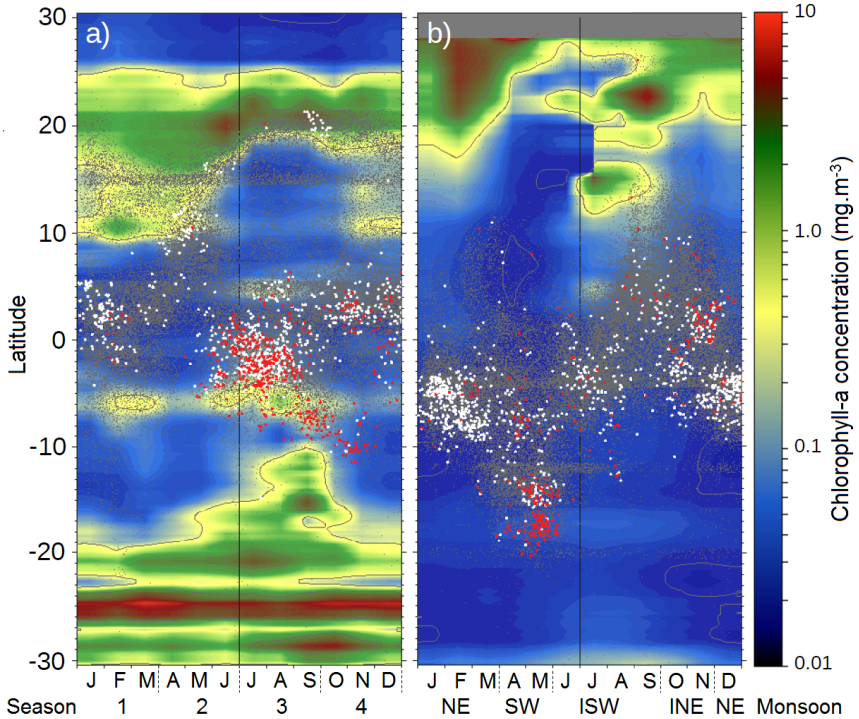


Figure 4.4 Chlorophyll-a concentration and latitudinal and seasonal locations of whale shark (red dots) and cetacean (white dots) sightings from 2002 to 2011, for a) the eastern tropical Atlantic Ocean and b) the western tropical Indian Ocean. Grey dots represent purse-seiner activities. Background colors represent the seasonality of chlorophyll-a concentration averaged over the envelope of longitudes of 4.1).

Eddy kinetic energy showed the exact inverse of chlorophyll-a, explaining a significant part of the model deviance in the WIO but not in the EAO. This may be due to the high values of this parameter in the Mozambique Channel and off Somalia (Appendix 4.F), related Tew-Kai and Marsac 2010). It is known that the edge of eddies provide high biological production that support large aggregation of micronekton, Tew-Kai and Marsac 2010).

While, in both oceans SST also played a significant role in the models, the range of observed temperature varied in each ocean. In the WIO, whale shark sightings mostly occurred between 27.5 and 29.5° 4.5 Sequeira *et al.* 2012), while in the EAO, most whale shark sightings were recorded between 22.6 and 26.5°C 4.5.a). In the waters off Gabon to Angola, SST was the lowest during season 2 and 3, Van Bennekom and Berger 1984) and corresponding to the peak in the presence of whale sharks. In general, whale sharks are considered to occur

Rowat and Brooks 2012 Sequeira *et al.* 2012), but here their highest co-occurrence with the purse-seine fishery was observed during periods when the SST values were lower than their reported preferred temperature range. This pattern may indicate that individual whale sharks could have a feeding advantage by being present in very productive areas rather than restricting their movements to warmer but less productive areas.

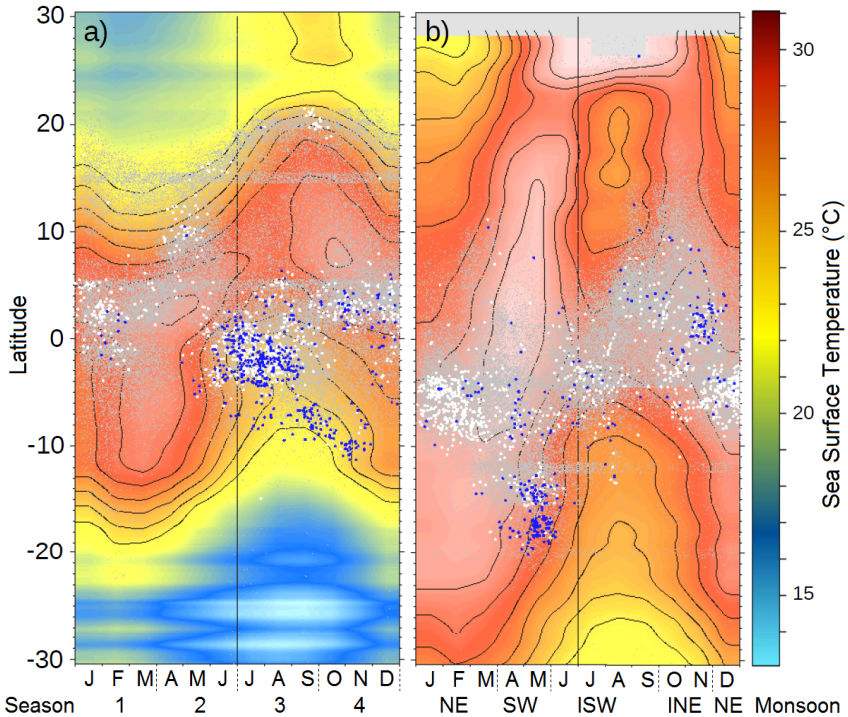


Figure 4.5 Sea Surface Temperature and latitudinal and seasonal locations of whale shark (blue dots) and cetacean (white dots) sightings from 2002 to 2011, for a) the eastern tropical Atlantic Ocean and b) the western tropical Indian Ocean. Grey dots represent purse-seiner activities. The background colors represent the seasonality of Sea Surface Temperature averaged over the envelope of longitudes 4.1).

4.4.2 Cetaceans

In both oceans, cetacean sightings recorded by purse-seine captains were mainly of large baleen whales (94%), which include four species: Bryde's whale, fin whale, sei whale, and humpback whale (based on observation from scientific observers). The number of dolphin sightings was too low to be further discussed.

In the WIO, depth explained a large part of the deviance in the model (21.2%). For instance, areas with higher predicted co-occurrence (e.g. around the Seychelles or the north of the Mozambique Channel), were part of the continental margin, in a depth range between 500 and 3000m. In the EAO, cetaceans and fishery co-occurrence were also slightly linked

to depth (e.g. the waters off Gabon to Angola and Mauritania to Senegal). Consequently, such environments may provide conditions that are suitable for both cetaceans and tuna, as was observed for whale sharks. Oceanic waters may be the preferred habitat for both species groups and shallower areas may have the advantage of receiving terrestrial inputs, which boost productivity. Consequently areas close to continental shelves, where coastal and oceanic habitats converge, may contain high densities of prey for both species groups.

In areas and seasons that showed high cetacean co-occurrence with tuna purse- 4.3 4.4.a and Appendix 4.F). Similarly to whale sharks, this variable was not significant at the scale of the 4.4.b) but areas with high fishery/cetacean co-occurrence also arise in productive areas. For SST, results were again similar to the whale sharks models. In the EAO the co-occurrence of cetaceans and the purse-seine fishery primarily predicted across a range of moderate SST values (22.0–27.0°C), while in the WIO, it was by SSTs between 4.3 4.5 and Appendix 4.F).

Similarly to the whale shark models, season was the second most important variable in the WIO, while it was of marginal relevance in the EAO. Cetaceans/fishery co-occurrence was highly prevalent during two specific seasons in the EAO, while in the WIO, patterns of 4.3) showed a closer reflection of the seasonal changes in purse-seine fishing grounds (Appendix 4.A) throughout the year. The inter-ocean difference in seasonal influence may thus be explained by different spatio-temporal fishing patterns. It is worth mentioning that cetaceans likely have a larger spatial distribution across the EAO and WIO than represented here, but our study was based on the co-occurrence with the surface tuna fisheries, and results are thus limited by their spatial extent.

Previous studies performed in waters along the coastline from Gabon to Angola found that Bryde's, humpback (the two most abundant cetacean species), fin and sei whales were Weir 2007 de Boer 2010). Bryde's whales Weir 2007 de Boer 2010). In addition, foraging behavior on schools of small pelagic fish, such as de Boer 2010). Humpback whales are also present from May to October, but primarily in shallow waters (< 200m) as they use the area as calving and mating grounds during winter, after feeding in the southern Weir 2007 de Boer 2010). The two other species of baleen whales, fin and sei whales, are also believed to undertake similar seasonal migrations between winter breeding Weir 2007). However, sei whale was considered the only species performing these seasonal migration and also feeding in winter Budker and Collignon 1952). All four baleen whale species also occur in

Robineau 1982 Mannocci *et al.* 2014).

Baleen whales and surface tuna schools may form foraging associations to feed on the Romanov 2002), a behaviour sometimes used by purse-seine fishers to improve their fishing success. This strategy may thus explain the high co-occurrence between baleen whales and purse-seine fisheries observed in areas that support high densities of prey common to both baleen whales and tunas. Tunas in surface aggregations feed primarily on epipelagic fishes, crustaceans and small cephalopods, such as the oceanic ligthfish (*Vinciguerria nimbaria*) or the bigeye cigarfish (*Cubiceps pauciradiatus* Bashmakov *et al.* 1991 Romanov 2002) and Bryde's whale, as mentioned above, also forage on pelagic de Boer 2010). Areas of high abundance of bigeye cigarfish in the WIO Potier *et al.* 2008) clearly overlap baleen whales hotspots identified in the present study. Additionally, similar distributions between whale-associated sets and bigeye cigarfish abundance estimated during trawl surveys have been found during the NE and IWS monsoon periods along the Seychelles-Chagos thermocline ridge (Romanov, unpublished data). This confirms the high co-occurrence of baleen whales and the tuna fishery in this productive environment and further reinforces previous assumptions of baleen whales and tuna feeding associations on shared prey species.

Conclusion

Due to the immensity of the open ocean environment, conducting large-scale scientific observation programs on all fishing vessels (i.e. 100% coverage) dedicated to the study of the co-occurrence between fisheries and megafauna species remains difficult. Fisheries-related data have inherent limitations, such as non-reporting or underreporting of interactions, and imprecise species identification. The use of a long-term dataset obtained from commercial fisheries, such as the logbooks from tropical tuna purse-seine vessels, is however of major interest for identifying seasons and regions of co-occurrence between fisheries and megafauna, and to explore the environmental conditions linked to this co-occurrence.

In summary, by implementing quantitative models including environmental variables, our study highlighted that high co-occurrence of both whale sharks and cetaceans with purse-seine fisheries were in productive areas during particular seasons. Other environmental variables reflecting the continental shelves (depth, slope and distance to land) or eddy kinetic energy also highlighted the link with productive environments. Whale sharks and cetaceans co-occurrence with fishery were also associated with SST, with both groups detected in lower SST ranges in the EAO than in the WIO. Finally, our results suggest that

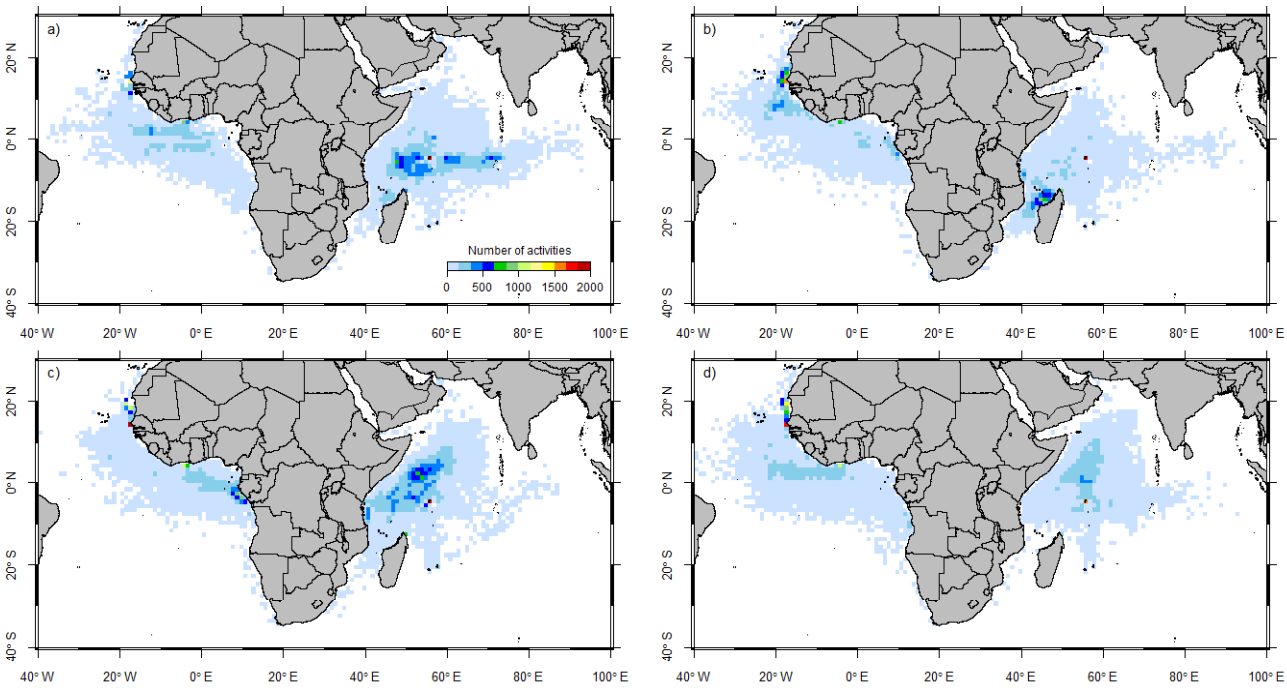
seasonal variability could have different effects in the EAO or WIO on the distribution of megafauna/fishery co-occurrence, with greater seasonal effects in our models in the WIO. The identification of areas and seasons linked to particular environmental condition with high co-occurrence of purse-seine fisheries and both whale sharks and cetaceans, described here, could facilitate conservation management measures for these species, such as ban of intentional encirclements in these specific areas and seasons.

Acknowledgements

We thank an anonymous reviewer for his constructive comments on an earlier version of the manuscript. We are grateful to the skippers and fishing companies involved in the logbook data collection (supported by IRD and IEO) and the teams of the "Observatoire Thonier" (IRD) and the "Centro Costero de Canarias" (IEO) for provided logbook data. The altimeter products were produced by Ssalto/Duacs and distributed by Aviso with support from CNES. L. Escalle is funded by a PhD grant from the University of Montpellier, and M.G. Pennino by the MORSE project (CEP&S 2011- Project ANR-11-CEPL-006, France). J.D. Filmalter has edited the English of the paper.

Appendix 4.A

Seasonal distribution of purse-seine sighting effort in the tropical eastern Atlantic and western Indian Oceans a) season 1 and NE monsoon, b) season 2 and ISW monsoon, c) season 3 and SW monsoon, and d) season 4 and INE monsoon.



Appendix 4.B

Model calibration for whale sharks in the Atlantic Ocean.

Table 4.B.1. GAM and BRT binomial models (presence/absence). Number in brackets indicate the percentage of the total deviance explained by each explanatory variables.

Models	Explanatory variables	% Deviance[1]	R^2	Correlation[2]	Moran p-value	Moran's I[3]
GAM binomial	SST, CHL, EKE, LandDist, Season, ti(EKE, LandDist)	22.4	0.14	0.38	$< 2.2e^{-16}$	0.14
GAM binomial RAC	SST, CHL, EKE, LandDist, Season, Autocovariate, ti(EKE, LandDist)	29.0	0.18	0.43	$< 2.2e^{-16}$	0.09
BRT binomial	CHL (8.4), SST (6.9), LandDist (5.0), Depth (2.7), EKE (2.7), Slope (2.6), Season (1.3)	29.3		0.49	$< 2.2e^{-16}$	0.12
BRT binomial RAC*	CHL (5.4), SST (4.4), LandDist (2.4), Depth (1.6), EKE (1.4), Season (1.0), Slope (0.2), Autocovariate (19.0)	35.5		0.51	$< 2.2e^{-16}$	0.06

[1] % Deviance explained by each model.
[2] Pearson correlation index between observed and predicted values.
[3] Moran's index maximum absolute value for each model.

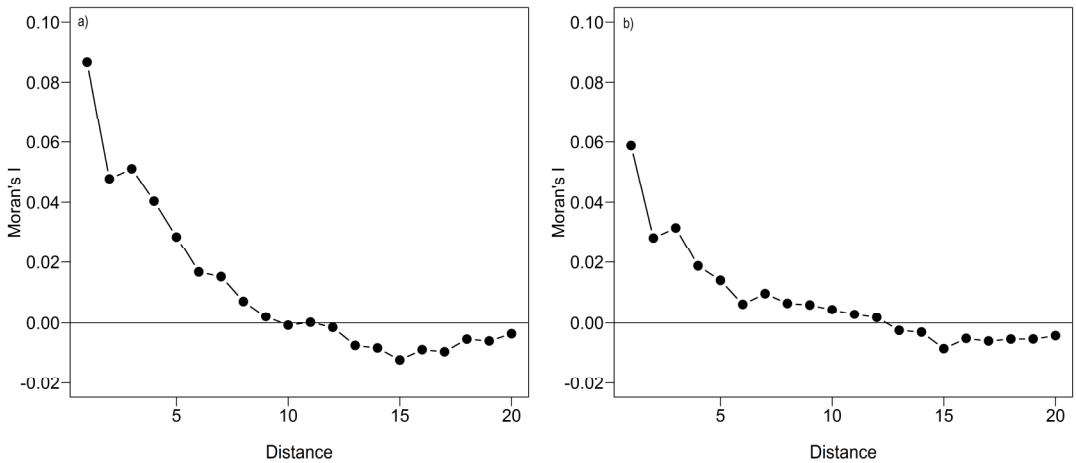


Figure 4.B.1. Correlograms of a) GAM binomial RAC and b) BRT binomial RAC models.

Cross validation

Binomial model performance was assessed using the area under the receiver-operating characteristic curve (AUC), and using specificity, sensitivity, and kappa derived from the confusion matrix. AUC allows occupied and unoccupied sites to be correctly distinguished. Specificity and sensitivity are the correctly classified proportion of true negatives and true positives respectively. They measure the model's ability to predict the presence or absence of a species according to the real occurrence of the species at a given location. Kappa measures the proportion of correctly classified locations, which is then compare to a threshold derived from the cross validation to convert these values into presence/absence predictions.

Table 4.B.2. Cross Validation parameters from GAM and BRT binomial RAC models.

	GAM binomial RAC*	BRT binomial RAC
Threshold	0.14	0.04
AUC	0.53	0.53
Kappa	0.02	0.01
Sensitivity	0.56	0.71
Specificity	0.50	0.35

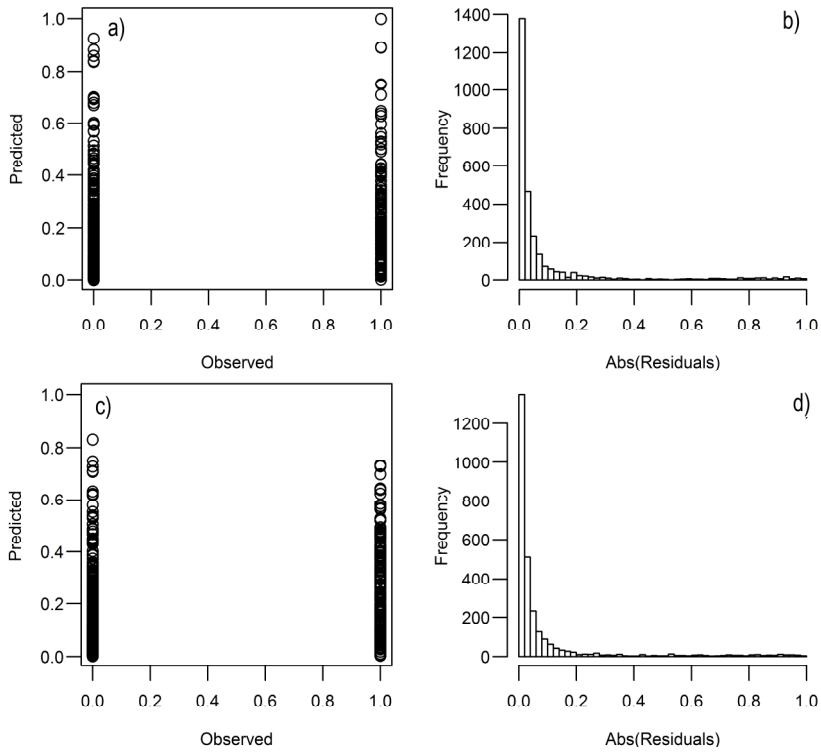


Figure 4.B.2. Graph of the predicted and observed values and histogram the absolute value of the residuals for a) b) GAM binomial RAC and c) d) BRT binomial RAC models.

Table 4.B.3. Statistics of observed and predicted values, and residuals of the binomial models (presence/ absence).

	Observed	GAM Binomial	GAM Binomial RAC	BRT Binomial	BRT Binomial RAC*
Observed or predicted values					
Mean	0.06	0.06	0.06	0.06	0.06
Median	0	0.02	0.02	0.03	0.02
Min	0	0	0	0	0
Max	1	1	1	0.65	0.83
Standard deviation	0.24	0.09	0.11	0.09	0.10
Residuals					
Mean		$1.82e^{-15}$	$-1.88e^{-15}$	$-5.54e^{-04}$	$-2.82e^{-04}$
Median		$-0.2e^{-02}$	-0.02	-0.02	-0.02
Standard deviation		0.22	0.21	0.21	0.20
Abs (residuals)					
Mean		0.10	0.09	0.09	0.09
Median		0.02	0.02	0.03	0.02
Standard deviation		0.20	0.19	0.19	0.18
(Residuals)2					
Mean		0.05	0.05	0.04	0.04
Median		$5.80e^{-04}$	$4.06e^{-04}$	$8.35e^{-04}$	$4.41e^{-04}$
Standard deviation		0.17	0.16	0.19	0.15

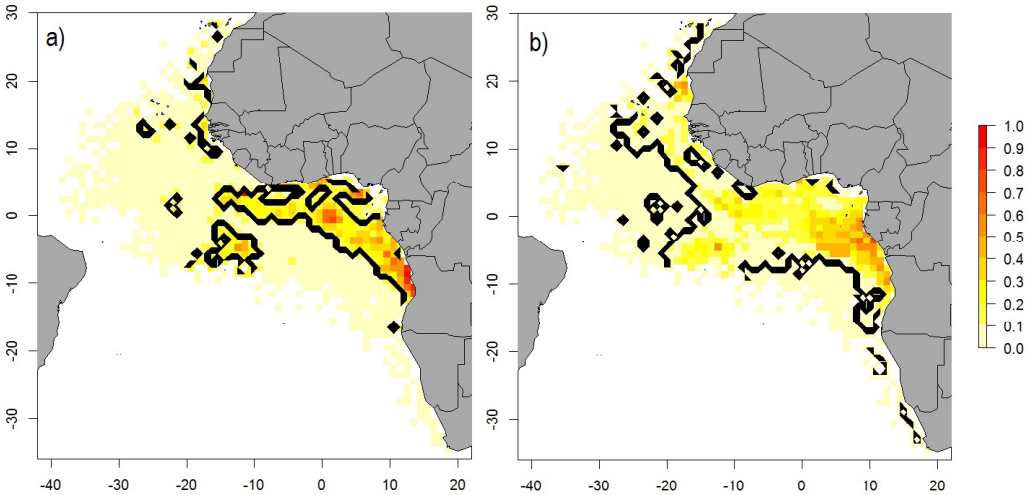


Figure 4.B.3. Envelope of presence/absence from a) GAM binomial RAC and b) BRT binomial RAC models.

Table 4.B.4. Count models (GAM quasi-poisson and BRT poisson). Number in brackets indicate the percentage of the total deviance explained by each explanatory variables.

Models	Explanatory variables	% Deviance	R^2	Correlation	Moran p-value	Moran's I
GAM quasi-poisson	SST, CHL, EKE, Depth, Slope, LandDist, Season	67.5	0.64	0.49	< 2.2e-16	0.15
GAM quasi-poisson RAC	SST, CHL, EKE, Depth, Slope, LandDist, Season, Autocovariate	81.0	0.75	0.54	$7.5e^{-14}$	0.05
BRT poisson	SST (22.1), CHL (14.9), LandDist (11.2), Depth (10.6), Slope (9.3), Season (1.3), EKE (1.2)	70.6		0.87	$< 2.2e^{-16}$	0.15
BRT poisson RAC*	CHL (5.5), LandDist (5.1), Slope (5.1), SST (3.5), Depth (3.5), Season (0.4), EKE (0.1), Autocovariate (59.7%)	83.0		0.94	0.06	0.02

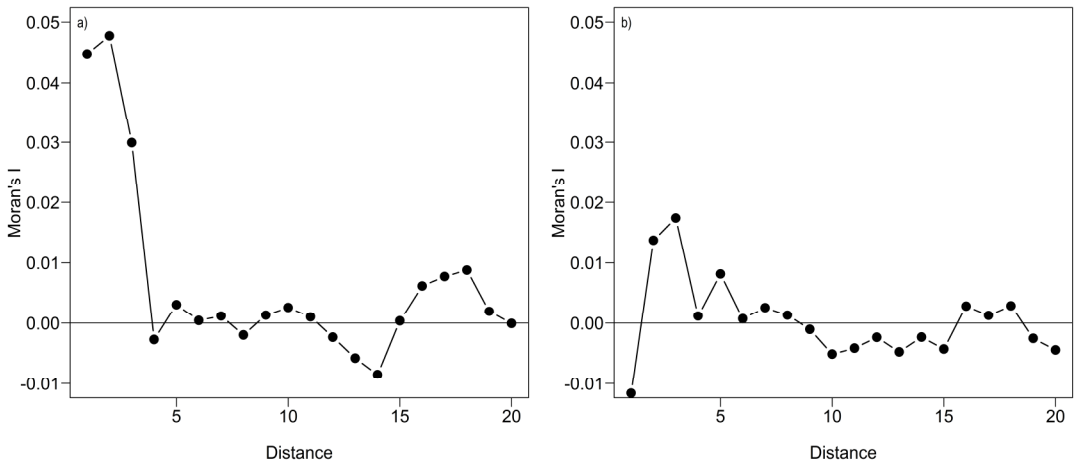


Figure 4.B.4. Correlograms of a) GAM quasi-poisson RAC and b) BRT poisson RAC models.

Table 4.B.5. Statistics of observed and predicted values, and residuals of the count models.

	Observed	GAM quasi-poisson	GAM quasi-poisson RAC	BRT poisson	BRT poisson RAC*
Observed or predicted values					
Mean	0.36	0.81	0.89	0.38	0.39
Median	0	0.08	0.14	0.05	0.04
Min	0	0	0	0	0
Max	49	53	59.7	60.8	59.9
Standard deviation	2.58	3.03	3.13	2.41	2.67
Residuals					
Mean		-0.44	-0.53	-0.02	-0.02
Median		-0.06	-0.10	-0.04	-0.03
Standard deviation		2.86	2.78	1.28	0.89
Abs (residuals)					
Mean		0.82	0.86	0.34	0.25
Median		0.09	0.14	0.05	0.04
Standard deviation		2.78	2.70	1.23	0.85
(Residuals)^2					
Mean		8.38	8.02	1.63	0.79
Median		0.01	0.02	$0.3e^{-02}$	$0.1\ e^{-02}$
Standard deviation		88.3	84.7	15.6	8.32

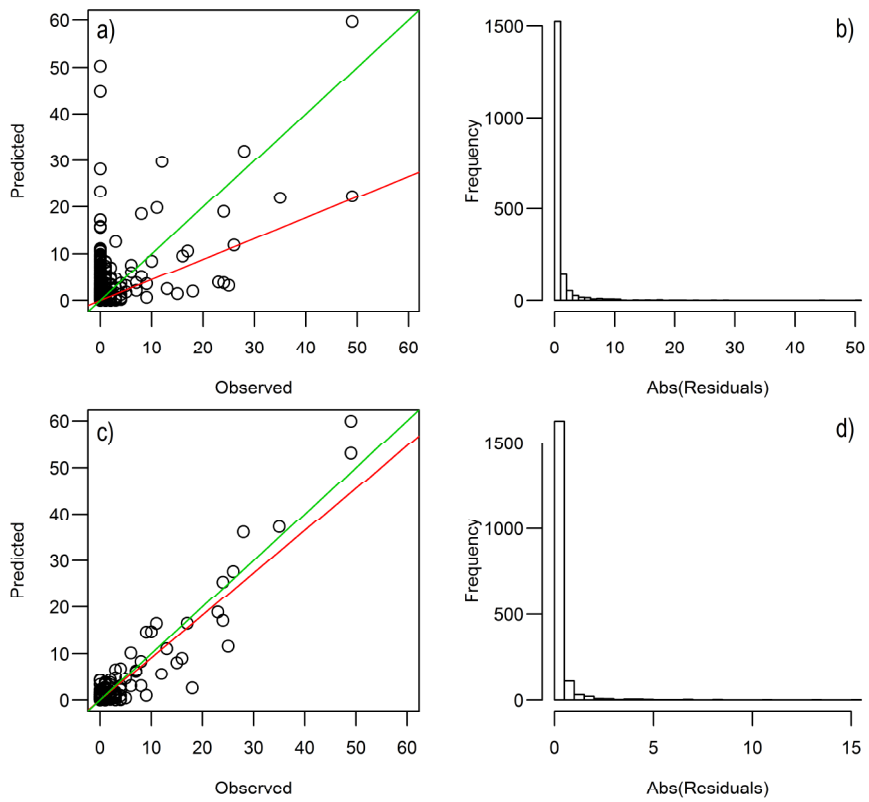


Figure 4.B.5. Graph of the predicted and observed values and histogram the absolute value of the residuals for a) b) GAM quasi-poisson RAC c) d) BRT poisson RAC models.

Appendix 4.C

Model calibration for whale sharks in the Indian Ocean.

Table 4.C.1. GAM and BRT binomial models (presence/absence). Number in brackets indicate the percentage of the total deviance explained by each explanatory variables.

	Explanatory variables	% Deviance[1]	R^2	Correlation[2]	Moran p-value	Moran's I[3]
GAM binomial	Depth, EKE, CHL, Season, ti(CHL, EKE)	10.4	0.05	0.24	$< 2.2e^{-16}$	0.12
GAM binomial RAC*	Depth, EKE, CHL, Season, Autocovariate, ti(CHL, EKE)	12.3	0.06	0.26	$< 2.2e^{-16}$	0.12
BRT binomial	EKE (5.8), CHL (5.2), Depth (3.1), Season (2.8), LandDist (2.5), SST (2.3), Slope (1.1)	22.9		0.20	$< 2.2e^{-16}$	0.01
BRT binomial RAC	EKE (5.0), CHL (4.7), Season (2.8), Depth (2.0), LandDist (2.0), SST (1.8), Slope (0.7), Autocovariate (5.2)	24.2		0.23	$< 2.2e^{-16}$	0.08

[1] % Deviance explained by each model.
[2] Pearson correlation index between observed and predicted values.
[3] Moran's index maximum absolute value for each model.

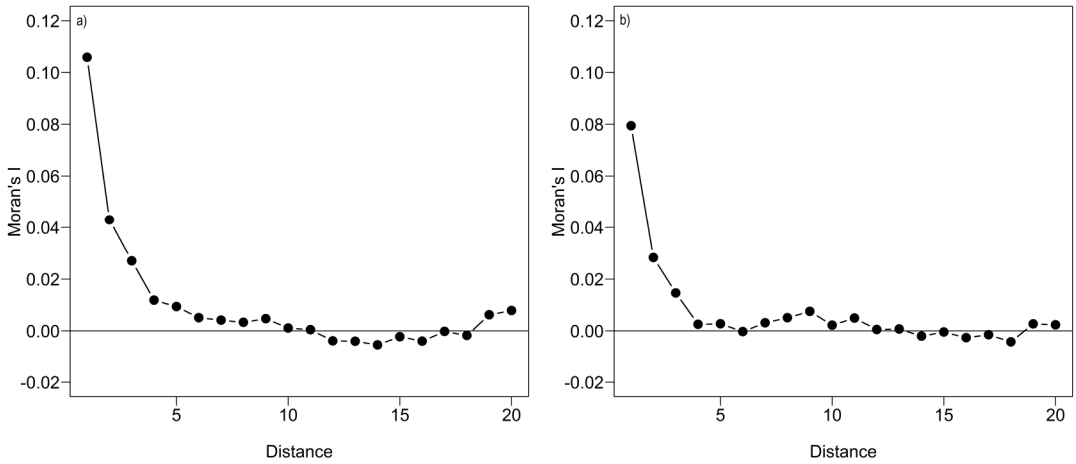


Figure 4.C.1. Correlograms of a) GAM binomial RAC and b) BRT binomial RAC models.

Cross validation

Binomial model performance was assessed using the area under the receiver-operating characteristic curve (AUC), and using specificity, sensitivity, and kappa derived from the confusion matrix. AUC allows occupied and unoccupied sites to be correctly distinguished. Specificity and sensitivity are the correctly classified proportion of true negatives and true positives respectively. They measure the model's ability to predict the presence or absence of a species according to the real occurrence of the species at a given location. Kappa measures the proportion of correctly classified locations, which is then compare to a threshold derived from the cross validation to convert these values into presence/absence predictions.

Table 4.C.2. Cross Validation parameters from GAM and BRT binomial RAC models.

	GAM binomial RAC*	BRT binomial RAC
Threshold	0.05	0.13
AUC	0.54	0.03
Kappa	0.01	0.32
Sensitivity	0.60	0.32
Specificity	0.46	0.74

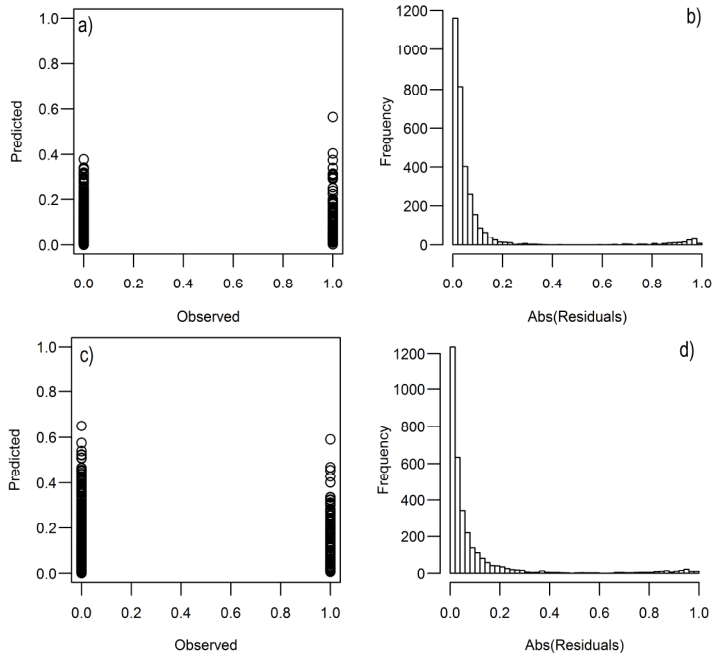


Figure 4.C.2. Graph of the predicted and observed values and histogram the absolute value of the residuals for a) b) GAM binomial RAC c) d) BRT binomial RAC models.

Table 4.C.3. Statistics of observed and predicted values, and residuals of the binomial models (presence/ absence)

	Observed	GAM binomial	GAM binomial RAC*	BRT binomial	BRT binomial RAC
Observed or predicted values					
Mean	0.05	0.05	0.05	0.06	0.06
Median	0	0.03	0.03	0.03	0.03
Min	0	0	0	0	0
Max	1	0.34	0.57	0.53	0.65
Standard deviation	0.21	0.04	0.05	0.07	0.08
Residuals					
Mean		$1.26e^{-15}$	$3.74e^{-16}$	-0.01	-0.01
Median		-0.03	-0.03	-0.03	-0.03
Standard deviation		0.20	0.21	0.21	0.21
Abs (residuals)					
Mean		0.08	0.08	0.09	0.09
Median		0.03	0.03	0.03	0.03
Standard deviation		0.18	0.18	0.19	0.18
(Residuals)^2					
Mean		0.04	0.04	0.04	0.04
Median		$9.58e^{-04}$	$8.30e^{-04}$	$9.90e^{-04}$	$9.75e^{-04}$
Standard deviation		0.17	0.17	0.16	0.16

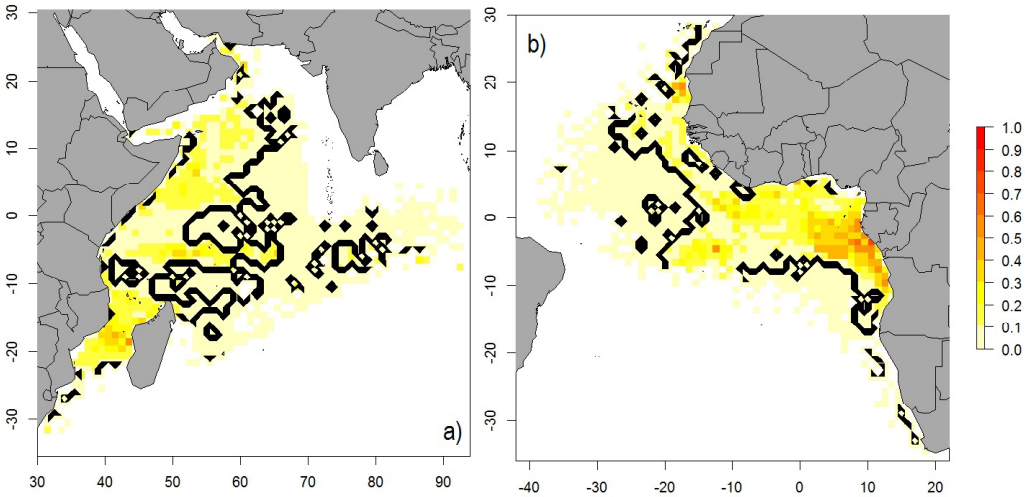


Figure 4.C.3. Envelope of presence/absence from a) GAM binomial RAC and b) BRT binomial RAC models.

Table 4.C.4. Count models (GAM quasi-poisson and BRT poisson). Number in brackets indicate the percentage of the total deviance explained by each explanatory variables.

Models	Explanatory variables	% Deviance	R^2	Correlation	Moran p-value	Moran's I
GAM quasi-poisson	SST, CHL, EKE, Depth, Season	43.7	0.43	0.35	0.02	0.07
GAM quasi-poisson RAC	SST, CHL, EKE, Depth, Season, Autocovariate	59.7	0.68	0.56	0.14	0.02
BRT poisson	Season (22.8), Depth (18.6), EKE (11.7), SST (7.3), CHL (5.8), Slope (1.1)	67.4		0.31	$0.20e^{-03}$	0.05
BRT poisson RAC*	Season (3.2), Depth (3.0), EKE (2.0), SST (1.1), CHL (0.5), Slope (0.1), Autocovariate (60.2)	70.1		0.54	$0.01e^{-02}$	0.03

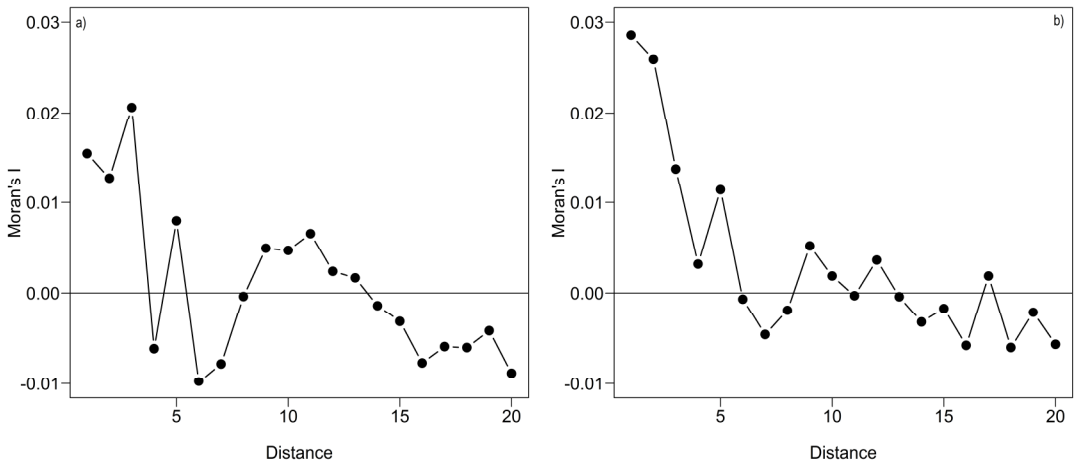


Figure 4.C.4. Correlograms of a) GAM quasi-poisson RAC and b) BRT poisson RAC models.

Table 4.C.5. Statistics of observed and predicted values, and residuals of the count models.

	Observed	GAM quasi-poisson	GAM quasi-poisson RAC	BRT poisson	BRT poisson RAC*
Observed or predicted values					
Mean	0.21	0.89	0.66	0.23	0.20
Median	0	0.37	0.28	0.05	0.04
Min	0	0	0	0	0
Max	36	23.0	31.2	3.9	10.2
Standard deviation	1.55	1.71	1.72	0.46	0.633
Residuals					
Mean		-0.64	-0.45	-0.02	0.01
Median		-0.34	-0.26	-0.03	-0.03
Standard deviation		1.86	1.55	1.47	1.32
Abs (residuals)					
Mean		0.87	0.66	0.36	0.30
Median		0.39	0.29	0.05	0.04
Standard deviation		1.76	1.47	1.43	1.28
(Residuals)^2					
Mean		3.87	2.59	2.17	1.74
Median		0.15	0.08	$0.20e^{-02}$	$0.10e^{-02}$
Standard deviation		24.90	27.99	32.70	24.30

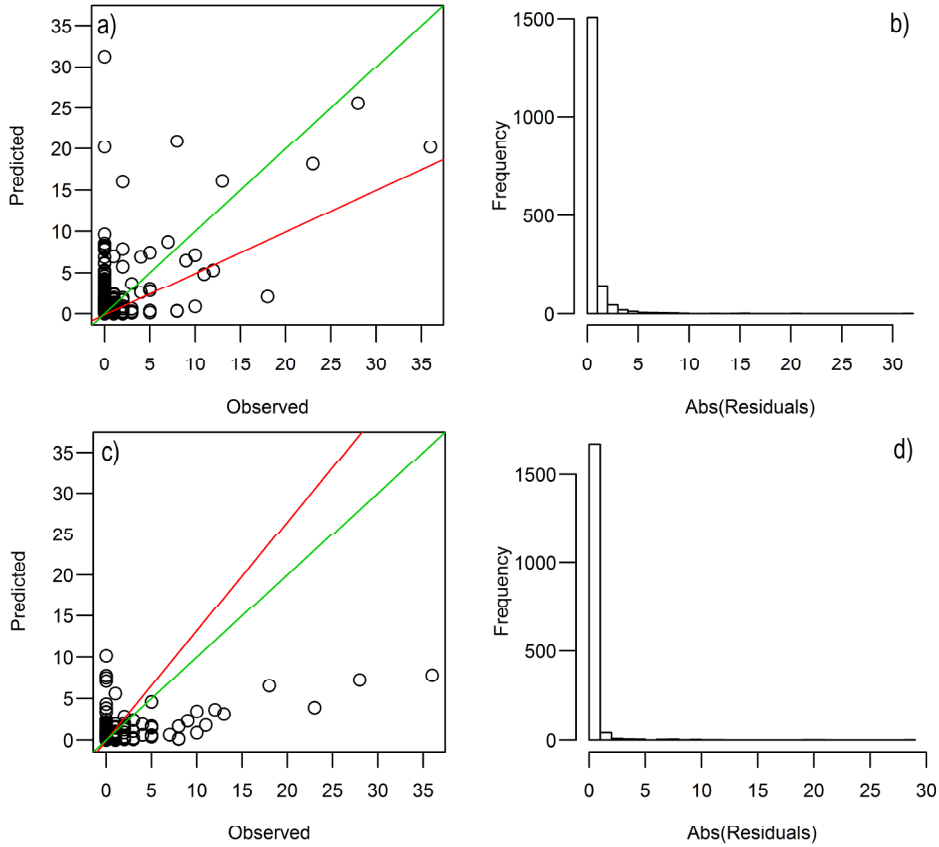


Figure 4.C.5. Graph of the predicted and observed values and histogram the absolute value of the residuals for a) b) GAM quasi-poisson RAC c) d) BRT poisson RAC models.

Appendix 4.D

Model calibration for cetaceans in the Atlantic Ocean.

Table 4.D.1. GAM and BRT binomial models (presence/absence). Number in brackets indicate the percentage of the total deviance explained by each explanatory variables.

Models	Explanatory variables	% Deviance[1]	R^2	Correlation[2]	Moran p-value	Moran's I[3]
GAM binomial	Depth, SST, CHL, EKE, Slope, LandDist, Season, ti(Depth,Slope)	15.6	0.12	0.35	$< 2.2e^{-16}$	0.18
GAM binomial RAC*	Depth, SST, CHL, EKE, Slope, LandDist, Season, Autocovariate, ti(Depth,Slope)	21.1	0.16	0.41	$1.2e^{-10}$	0.15
BRT binomial	LandDist (6.3), EKE (4.6), Slope (4.0), Depth (3.0), SST (2.4), CHL (2.3), Season (0.3)	23.0		0.46	$< 2.2e^{-16}$	0.16
BRT binomial RAC	LandDist (4.7), CHL (3.2), EKE (3.1), SST (2.5), Slope (1.8), Depth (1.5), Season (0.1), Autocovariate (11.3)	28.1		0.50	$< 2.2e^{-16}$	0.12

[1] % Deviance explained by each model.
[2] Pearson correlation index between observed and predicted values.
[3] Moran's index maximum absolute value for each model.

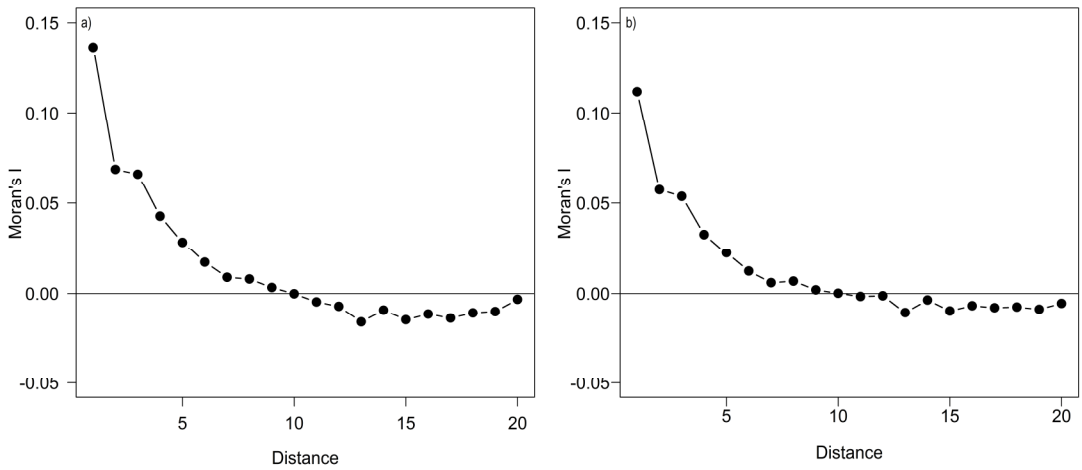


Figure 4.D.1. Correlograms of a) GAM binomial RAC and b) BRT binomial RAC models.

Cross validation

Binomial model performance was assessed using the area under the receiver-operating characteristic curve (AUC), and using specificity, sensitivity, and kappa derived from the confusion matrix. AUC allows occupied and unoccupied sites to be correctly distinguished. Specificity and sensitivity are the correctly classified proportion of true negatives and true positives respectively. They measure the model's ability to predict the presence or absence of a species according to the real occurrence of the species at a given location. Kappa measures the proportion of correctly classified locations, which is then compare to a threshold derived from the cross validation to convert these values into presence/absence predictions.

Table 4.D.2. Cross Validation parameters from GAM and BRT binomial RAC models.

	GAM binomial RAC*	BRT binomial RAC
Threshold	0.10	0.15
AUC	0.54	0.54
Kappa	0.04	0.06
Sensitivity	0.65	0.58
Specificity	0.44	0.53

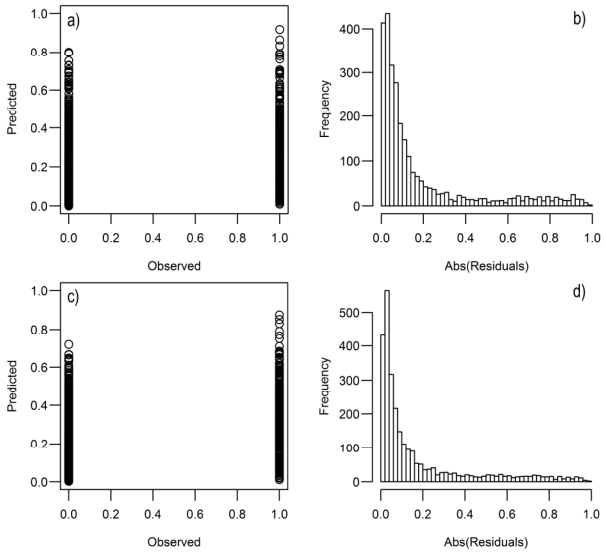


Figure 4.D.2. Graph of the predicted and observed values and histogram the absolute value of the residuals for a) b) GAM binomial RAC and c) d) BRT binomial RAC models.

Table 4.D.3. Statistics of observed and predicted values, and residuals of the binomial models (presence/ absence).

	Observed	GAM Binomial	GAM Binomial RAC*	BRT Binomial	BRT Binomial RAC
Observed or predicted values					
Mean	0.13	0.13	0.13	0.13	0.13
Median	0	0.09	0.07	0.08	0.07
Min	0	0	0	0	0
Max	1	0.85	0.92	0.79	0.86
Standard deviation	0.33	0.11	0.14	0.12	0.14
Residuals					
Mean		$2.21e^{-15}$	$-6.97e^{-16}$	$-6.79e^{-04}$	$-4.87e^{-04}$
Median		-0.01	-0.01	-0.06	-0.04
Standard deviation		0.31	0.30	0.30	0.29
Abs (residuals)					
Mean		0.19	0.18	0.18	0.17
Median		0.01	0.08	0.09	0.07
Standard deviation		0.21	0.24	0.23	0.23
(Residuals)2					
Mean		0.10	0.09	0.09	0.08
Median		0.01	0.01	0.01	$0.40e^{-02}$
Standard deviation		0.21	0.20	0.19	0.19

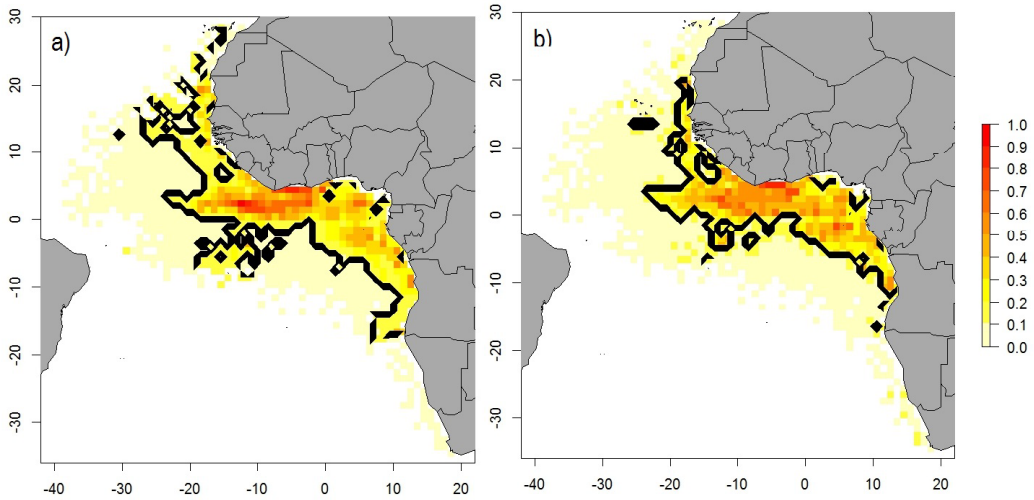


Figure 4.D.3. Envelope of presence/absence from a) GAM binomial RAC and b) BRT binomial RAC models.

Table 4.D.4. Count models (GAM quasi-poisson and BRT poisson). Number in brackets indicate the percentage of the total deviance explained by each explanatory variables.

Models	Explanatory variables	% Deviance	R^2	Correlation	Moran p-value	Moran's I
GAM quasi-poisson	SST, CHL, EKE, Depth, Season, Slope	53.3	0.58	0.45	$<2.2e^{-16}$	0.12
GAM quasi-poisson RAC	SST, CHL, EKE, Depth, Season, Slope, Autocovariate	65.5	0.78	0.58	0.11	0.06
BRT poisson	SST (27.0), Slope (12.5), CHL (12.0), Depth (10.1), LandDist (2.8), Season (2.7), EKE (1.5)	68.7		0.91	$<2.2e^{-16}$	0.09
BRT poisson RAC*	SST (7.6), CHL (6.6), Slope (3.7), Depth(1.9), Season (0.6), EKE (0.6), LandDist (0.5), Autocovariate (50.6)	72.1		0.92	$0.10e^{-02}$	-0.02

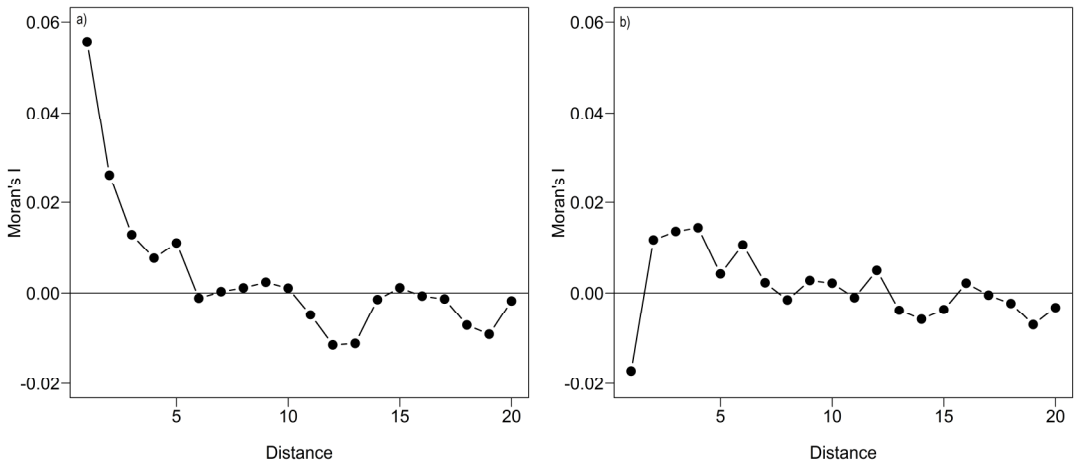


Figure 4.D.4. Correlograms of a) GAM quasi-poisson RAC and b) BRT poisson RAC models.

Table 4.D.5. Statistics of observed and predicted values, and residuals of the count models.

	Observed	GAM quasi-poisson	GAM quasi-poisson RAC	BRT poisson	BRT poisson RAC*
Observed or predicted values					
Mean	0.72	1.93	2.25	0.72	0.72
Median	0	0.82	1.15	0.22	0.21
Min	0	0.01	0.04	0	0
Max	81	49.8	66.0	71.1	72.9
Standard deviation	3.42	3.42	3.69	2.82	2.84
Residuals					
Mean		-1.20	-1.53	0.01	0.01
Median		-0.65	-0.92	-0.11	-0.12
Standard deviation		3.61	3.30	1.44	1.42
Abs (residuals)					
Mean		1.93	2.08	0.62	0.58
Median		0.85	1.13	0.22	0.21
Standard deviation		3.28	2.98	1.30	1.29
(Residuals)^2					
Mean		14.45	13.20	2.07	2.00
Median		0.72	1.27	0.05	0.04
Standard deviation		93.5	57.39	14.22	17.03

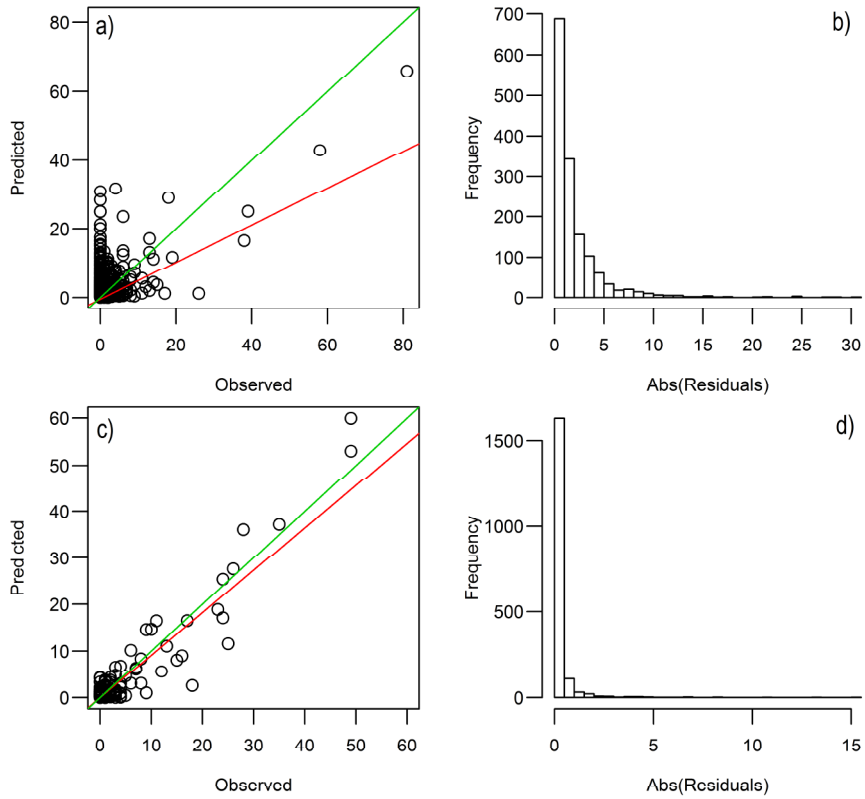


Figure 4.D.5. Graph of the predicted and observed values and histogram the absolute value of the residuals for a) b) GAM quasi-poisson RAC c) d) BRT poisson RAC models.

Appendix 4.E

Model calibration for whale sharks in the Indian Ocean.

Table 4.E.1. GAM and BRT binomial models (presence/absence). Number in brackets indicate the percentage of the total deviance explained by each explanatory variables.

Models	Explanatory variables	% Deviance[1]	R^2	Correlation[2]	Moran p-value	Moran's I[3]
GAM binomial	Depth, SST, EKE, CHL, LandDist, Season, ti(CHL, SST)	13.8	0.10	0.33	$< 2.2e^{-16}$	0.25
GAM binomial RAC	Depth, SST, EKE, CHL, LandDist, Season, Autocovariate, ti (Chla, SST)	19.8	0.18	0.43	$< 2.2e^{-16}$	0.20
BRT binomial	CHL (6.9), SST (4.8), EKE (3.9) LandDist (3.8), Depth (2.3), Slope (1.0), Season (0.5)	23.2		0.43	$< 2.2e^{-16}$	0.23
BRT binomial RAC*	CHL (5.5), SST (3.2), EKE (2.1), LandDist (3.8), Depth (1.8), Slope (0.5), Season (0.2), Autocovariate (15.0)	30.2		0.53	$< 2.2e^{-16}$	0.15

[1] % Deviance explained by each model.
[2] Pearson correlation index between observed and predicted values.
[3] Moran's index maximum absolute value for each model.

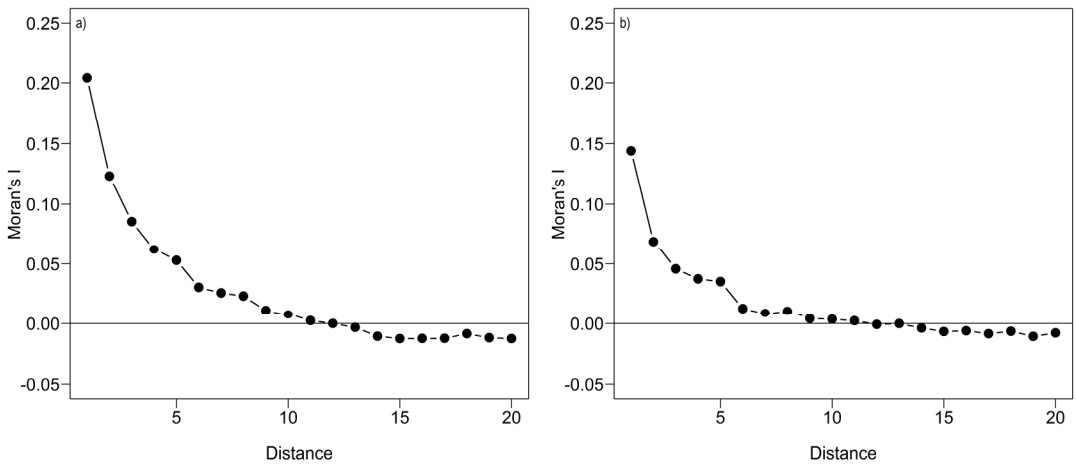


Figure 4.E.1. Correlograms of a) GAM binomial RAC and b) BRT binomial RAC models.

Cross validation

Binomial model performance was assessed using the area under the receiver-operating characteristic curve (AUC), and using specificity, sensitivity, and kappa derived from the confusion matrix. AUC allows occupied and unoccupied sites to be correctly distinguished. Specificity and sensitivity are the correctly classified proportion of true negatives and true positives respectively. They measure the model's ability to predict the presence or absence of a species according to the real occurrence of the species at a given location. Kappa measures the proportion of correctly classified locations, which is then compare to a threshold derived from the cross validation to convert these values into presence/absence predictions.

Table 4.E.2. Cross Validation parameters from GAM and BRT binomial RAC models.

	GAM binomial RAC*	BRT binomial RAC
Threshold	0.14	0.14
AUC	0.53	0.54
Kappa	0.05	0.05
Sensitivity	0.62	0.62
Specificity	0.47	0.46

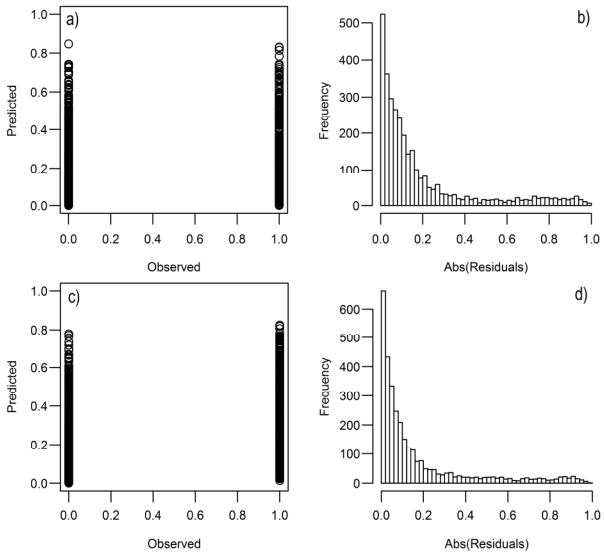


Figure 4.E.2. Graph of the predicted and observed values and histogram the absolute value of the residuals for a) b) GAM binomial RAC and c) d) BRT binomial RAC models.

Table 4.E.3. Statistics of observed and predicted values, and residuals of the binomial models (presence/ absence).

	Observed	GAM Binomial	GAM Binomial RAC	BRT Binomial	BRT Binomial RAC*
Observed or predicted values					
Mean	0.13	0.13	0.13	0.13	0.13
Median	0	0.11	0.09	0.09	0.07
Min	0	0	0	0	0
Max	1	0.64	0.85	0.64	0.83
Standard deviation	0.34	0.11	0.14	0.12	0.16
Residuals					
Mean		$9.41e^{-15}$	$-3.81e^{-14}$	$3.94e^{-04}$	$1.40e^{-03}$
Median		-0.01	-0.01	-0.06	-0.05
Standard deviation		0.32	0.31	0.31	0.29
Abs (residuals)					
Mean		0.21	0.19	0.19	0.17
Median		0.12	0.09	0.1	0.07
Standard deviation		0.25	0.24	0.24	0.23
(Residuals)2					
Mean		0.10	0.09	0.09	0.08
Median		0.01	0.01	0.01	0.01
Standard deviation		0.21	0.21	0.19	0.19

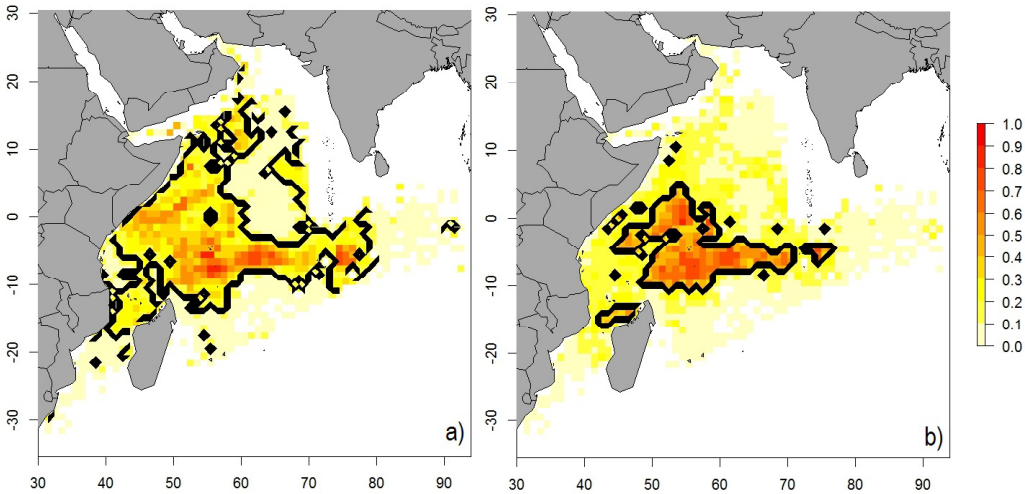


Figure 4.E.3. Envelope of presence/absence from a) GAM binomial RAC and b) BRT binomial RAC models.

Table 4.E.4. Count models (GAM quasi-poisson and BRT poisson). Number in brackets indicate the percentage of the total deviance explained by each explanatory variables.

Models	Explanatory variables	% Deviance	R^2	Correlation	Moran p-value	Moran's I
GAM quasi-poisson	Slope, SST, CHL, EKE, LandDist, Depth, Season	36.5	0.35	0.35	$2.99e^{-07}$	0.12
GAM quasi-poisson RAC	Slope, SST, CHL, EKE, LandDist, Depth, Season, Autocovariate	50.7	0.50	0.51	0.86	0.05
BRT poisson	Depth (38.3), Season (9.8), SST (4.6), Slope (4.5), CHL (3.7), LandDist (1.8), EKE (1.7)	64.3		0.69	1.00	0.08
BRT poisson RAC*	Depth (21.2), Season (4.3), Slope (3.0), SST (3.0), CHL (0.8), EKE (0.5), LandDist (0.3), Autocovariate (35.7)	68.2		0.77	0.28	

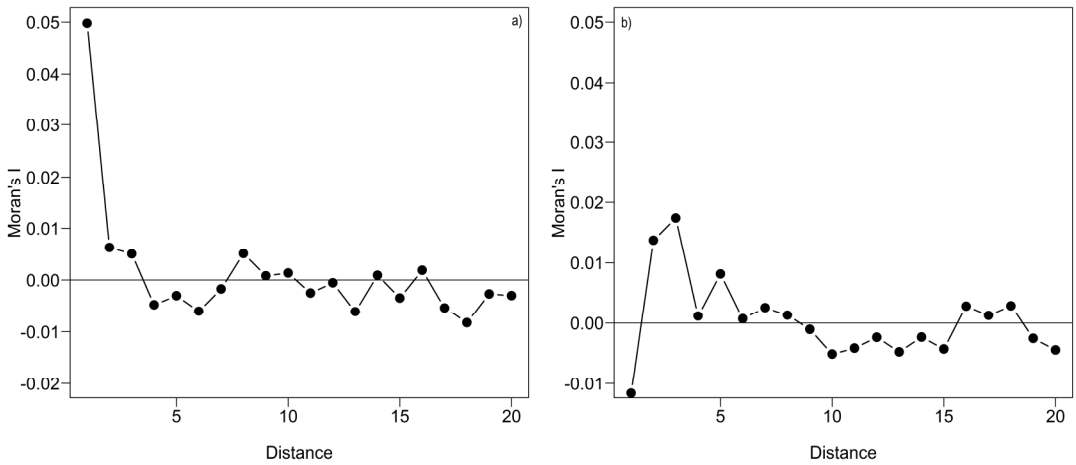


Figure 4.E.4: Correlograms of a) GAM quasi-poisson RAC and b) BRT poisson RAC models.

Table 4.E.5. Statistics of observed and predicted values, and residuals of the count models.

	Observed	GAM quasi-poisson	GAM quasi-poisson RAC	BRT poisson	BRT poisson RAC*
Observed or predicted values					
Mean	0.75	1.94	1.64	0.62	0.6
Median	0	1.41	1.03	0.20	0.18
Min	0	0	0.01	0	0
Max	38	22.8	23.3	12.0	19.2
Standard deviation	2.44	1.97	2.06	1.03	1.25
Residuals					
Mean		-1.19	-0.89	0.13	0.10
Median		-1.10	-0.77	-0.09	-0.08
Standard deviation		5.54	2.24	1.89	1.68
Abs (residuals)					
Mean		1.83	1.50	0.71	0.65
Median		1.27	0.94	0.20	0.18
Standard deviation		2.13	1.89	1.76	1.55
(Residuals)^2					
Mean		7.88	5.82	3.58	2.83
Median		1.61	0.88	0.04	0.03
Standard deviation		29.76	22.30	27.46	19.96

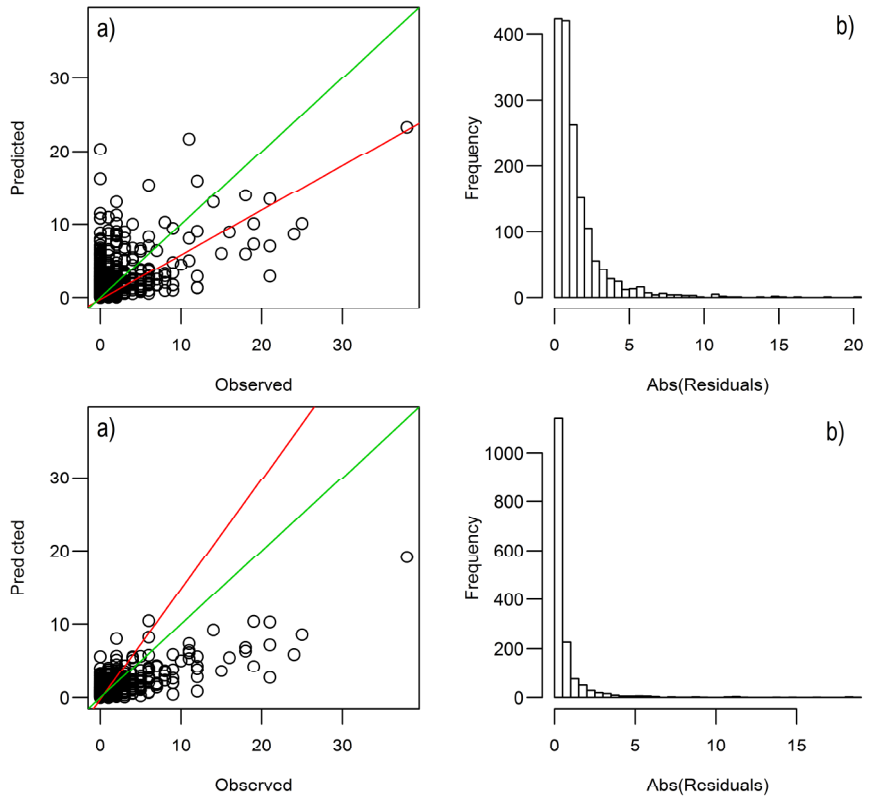


Figure 4.E.5. Graph of the predicted and observed values and histogram the absolute value of the residuals for a) b) GAM quasi-poisson RAC c) d) BRT poisson RAC models.

Appendix 4.F

Environmental factors

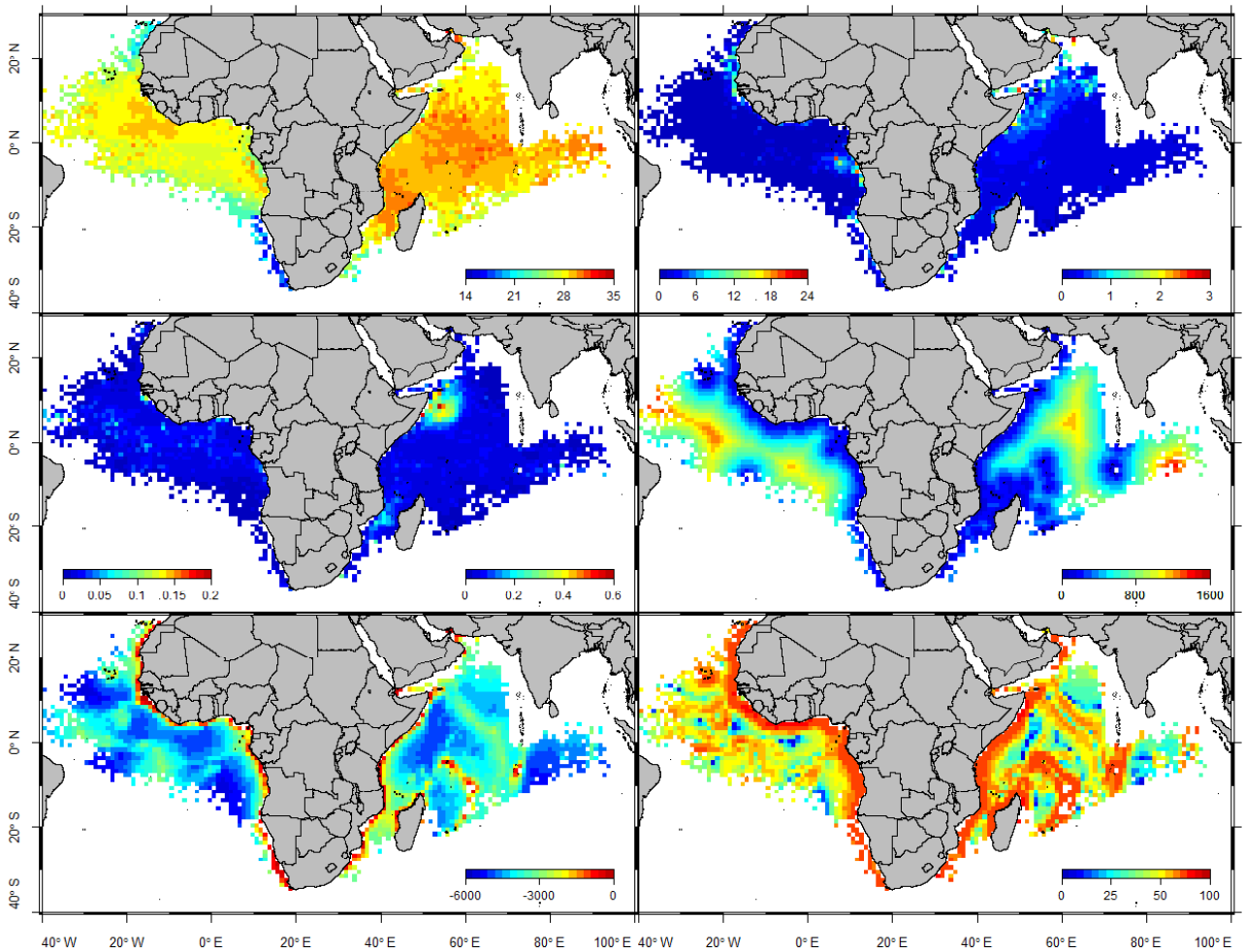


Figure 4.F.1. a) Sea Surface Temperature (°C), b) Chlorophyll-a concentration (mg.m^{-3}), c) Eddy Kinetic Energy (m^2.s^2), d) Distance to land (km), e) Depth (m), and f) slope (%).

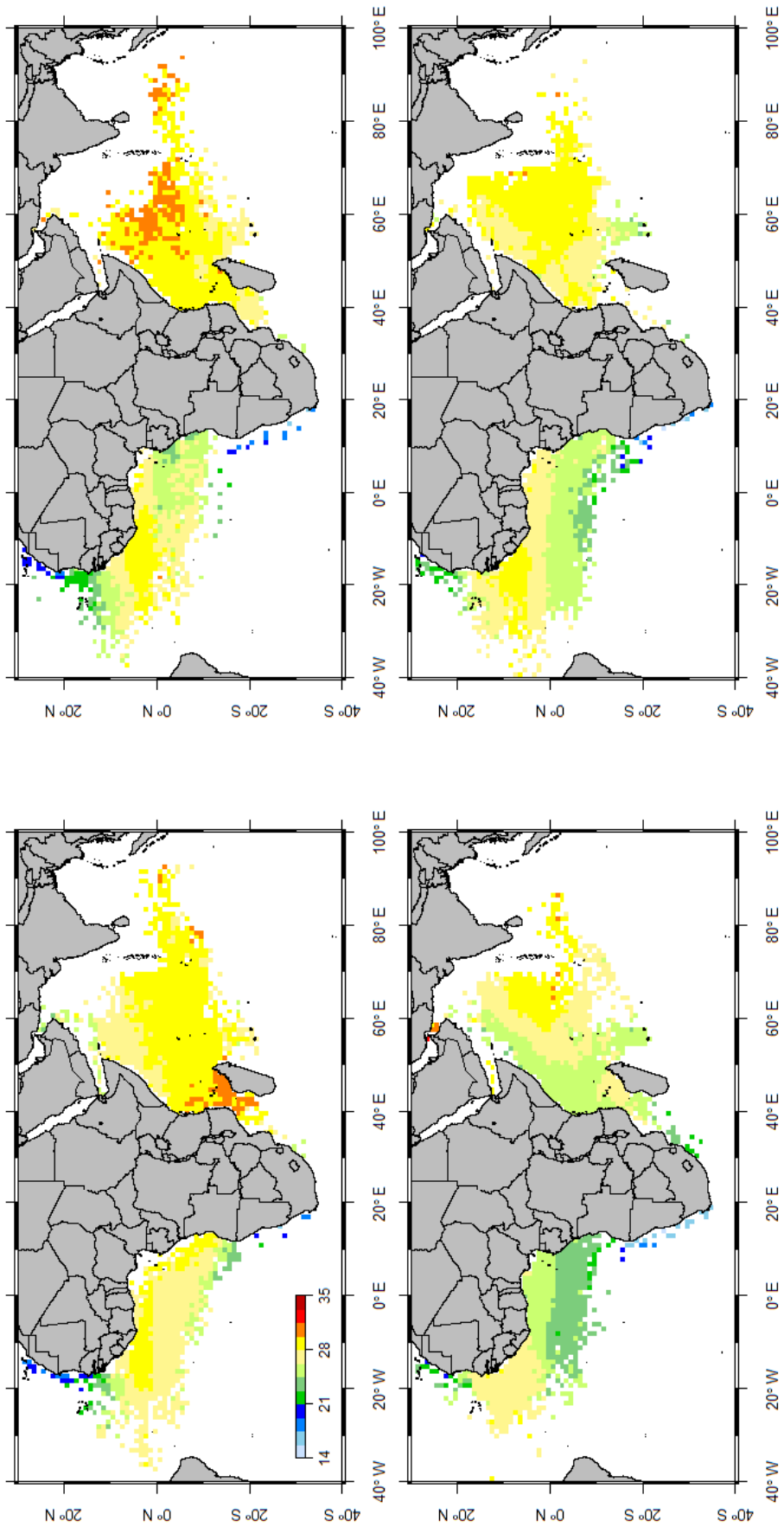


Figure 4.F.2. Sea Surface Temperature (°C) seasonal variability in the eastern Atlantic and western Indian Oceans: a) Season 1 and north-east (NE) monsoon, b) Season 2 and intermediate south-west (ISW) monsoon, c) Season 3 and south-west (SW) monsoon, and d) Season 4 and intermediate north-east (INE) monsoon.

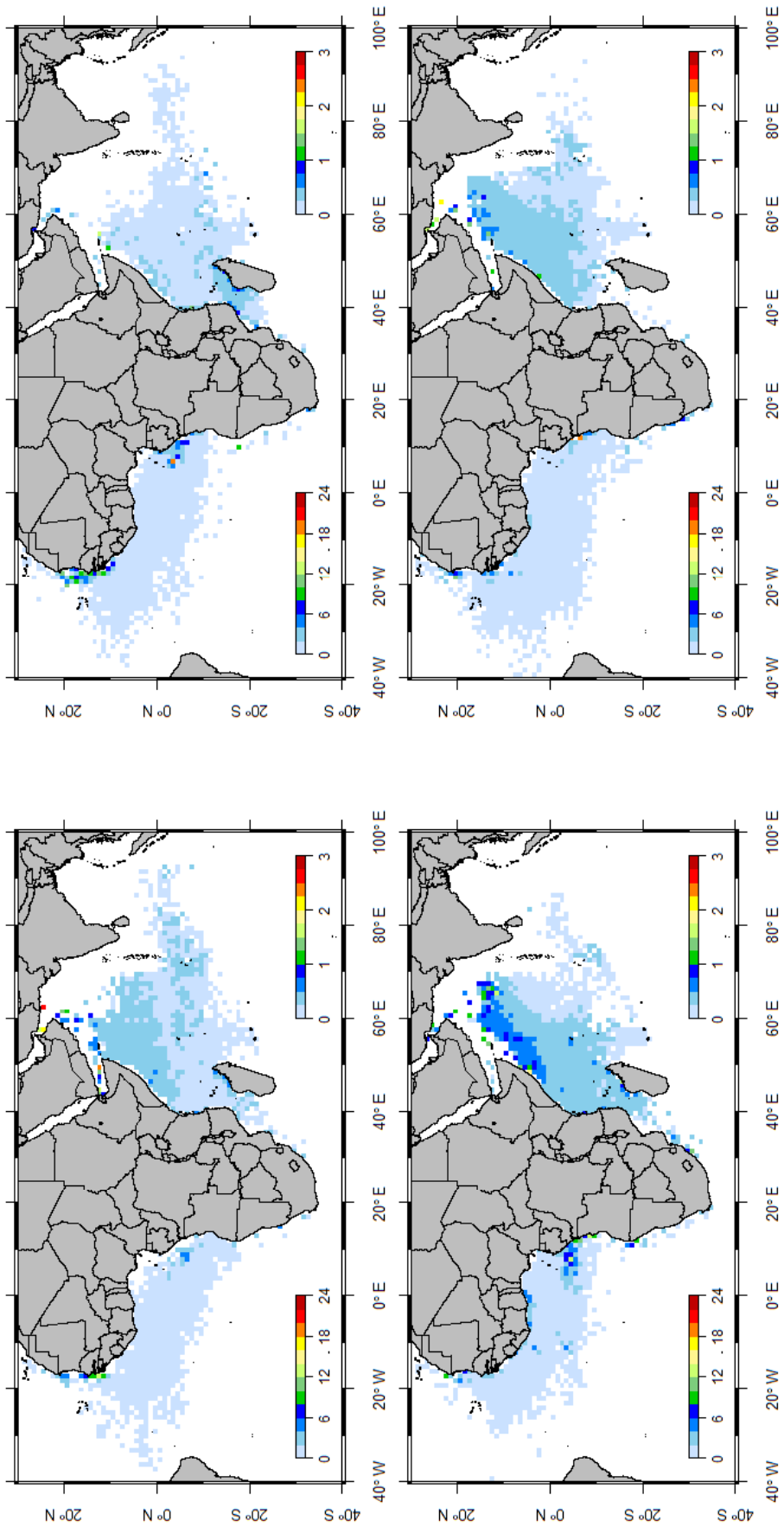


Figure 4.F.3. Chlorophyll-a concentration (mg.m^{-3}) seasonal variability in the eastern Atlantic and western Indian Oceans: a) Season 1 and NE monsoon, b) Season 2 and ISW monsoon, c) Season 3 and SW monsoon, and d) Season 4 and INE monsoon.

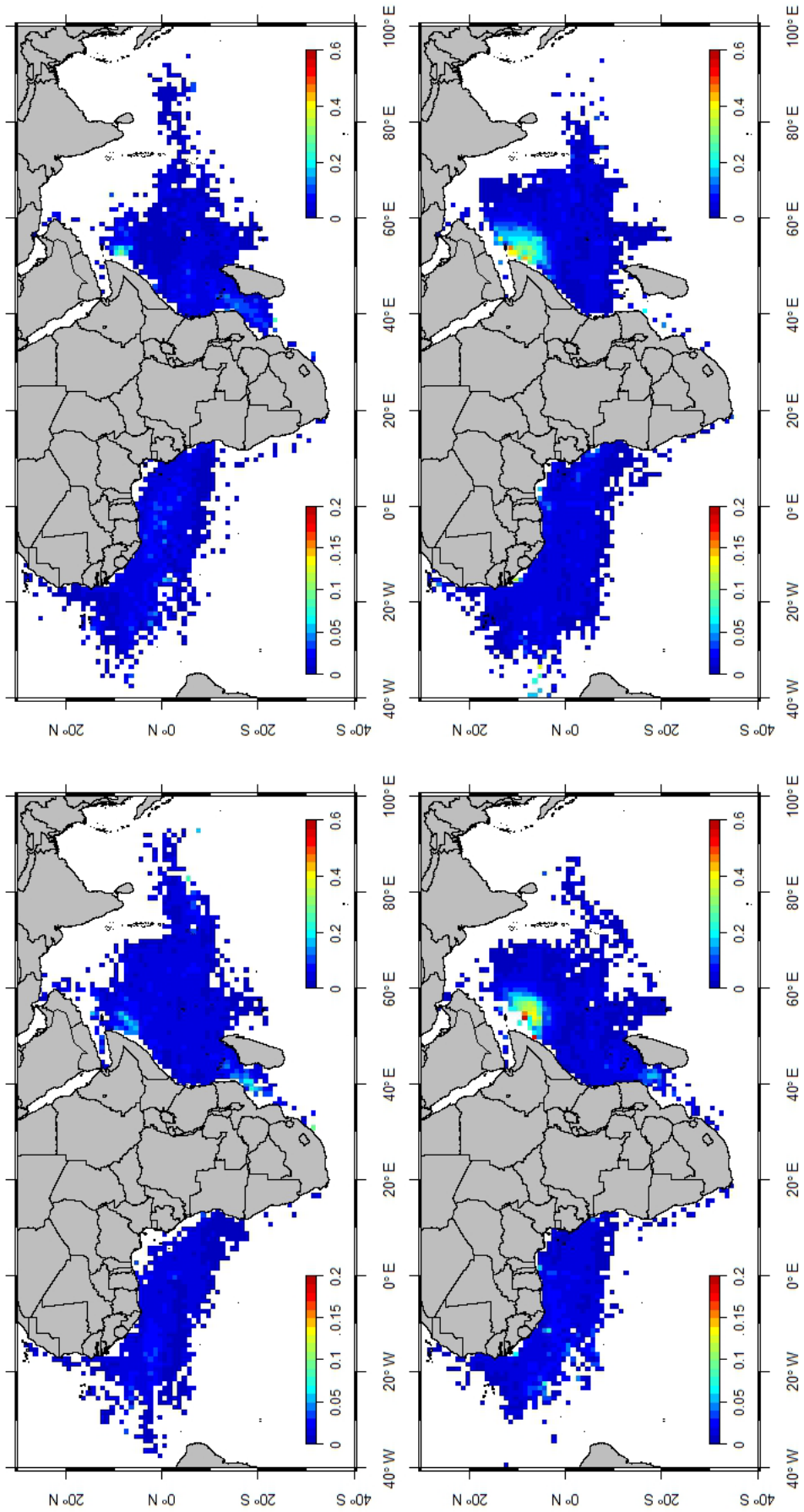


Figure 4.F4. Eddy Kinetic Energy ($m^2.s^2$) seasonal variability in the eastern Atlantic and western Indian Oceans: a) Season 1 and NE monsoon, b) Season 2 and ISW monsoon, c) Season 3 and SW monsoon, and d) Season 4 and INE monsoon.

In the previous chapters, main areas of co-occurrence and interactions between whale sharks, cetaceans and the tuna purse-seine fishery have been identified and found to be linked to highly productive areas. In addition, the European purse-seine fishery has a relatively low apparent impact on whale sharks and cetaceans. However, it is now relevant to also investigate other species associated with encircled megafauna species. This may be relevant for stock assessment purposes, as well as fishing statistics but also to investigate the whole species assemblage captured by the purse-seine fishery. It has been previously identified that the interactions between the purse-seine fishery and megafauna species mostly involve, in both oceans, whale sharks and baleen whales. Therefore, in the following chapters, we will focus on these two megafauna associated fishing sets. The investigation of the species assemblage associated with whale sharks and baleen whales will involve investigation of species and size composition of targeted tuna species, as well as diversity of the bycatch species. To characterize the species associated with whale sharks and baleen whales, a comparison with the two other fishing modes performed in the eastern Atlantic and western Indian Ocean, FAD and free school sets, will been preformed. Such study may be important for tuna management and fishing statistics, but also to increase knowledge on pelagic inter-specific associations.

Chapter 5

Targeted and bycatch species assemblage captured in whale and whale shark associated sets

Catch and bycatch of the tropical tuna purse-seine fishery in whale and whale shark associated sets: comparison with free school and FAD sets

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In Preparation for Biodiversity and Conservation (Article 5)

Escalle, L., Simier, M., Gaertner, D., Chavance, P., Murua, H., Alayon P. P., Ménard, F., Abascal, F., Ruiz, J., Mérigot, B. Catch and bycatch captured by tropical tuna purse-seine fishery in whale and whale shark associated set: comparison with free school and FAD sets. Biodiversity and Conservation

Abstract

In the framework of an Ecosystem Approach to Fisheries (EAF) management, assessment of targeted species composition in tuna purse-seine fishery, but also those of bycatch species is essential. In the Atlantic and Indian Oceans, purse-seine nets are sometimes sets around tuna schools associated with whale sharks and baleen whales, although less frequently than on free swimming tuna schools or those associated with natural or artificial Fish Aggregating Devices (FAD). However, data on the targeted catch and bycatch on these megafauna associated fishing sets are still relatively very limited. Nowadays, such information may be necessary for stock assessment purposes, but also to investigate the whole fish assemblage captured. Therefore the aims of this study are to assess abundance and weight of tuna species and their size composition, as well as bycatch diversity, for species captured in association with baleen whales and whale sharks. Whale associated sets were found to be very similar to free school sets, in terms of tuna catch (large yellowfin tuna), bycatch occurrence (half the sets) and species assemblage (alpha and beta diversity). Whale shark associated sets were intermediate between FAD and free school sets, with tuna catch (skipjack and juvenile yellowfin) and bycatch occurrence closer to FAD than to free school sets. However, the presence of large yellowfin and the bycatch composition (no finfish abundantly captured in FAD sets) and species assemblage showed similarity with free school sets. Interestingly, both megafauna associated sets have higher capture rates of vulnerable species, such as silky sharks (main bycatch species in both sets) or manta rays (4–7% occurrence). Therefore this study contributes to an EAF management in the tuna purse-seine fishery, but also to increase the knowledge on pelagic multi-specific catches and bycatches.

Key words

Megafauna, bycatch, diversity, targeted catch, tuna purse-seine fishery, Ecosystem Approach to Fisheries

5.1 Introduction

Recently, fishery management has evolved from mostly single (or few) targeted FAO 2003 Pikitch *et al.* 2004. This approach recognizes that fisheries not only affect targeted species, but also other species Ward *et al.* 2002). Therefore it calls for integration of these aspects in fishery management, in order to account FAO 2003).

In the open ocean, tropical purse-seiners locate tuna schools at the surface of the sea through the detection of visual cues. These may include flocks of birds, surface water deformation, various floating objects or the presence of megafauna species (e.g. whale shark *Rhincodon typus*). In the eastern Atlantic (EAO) and western Indian Oceans (WIO), for data management purposes, four fishing modes are identified: sets made around free swimming tuna schools ("free school sets"), sets made on Fish Aggregating Devices ("FAD sets"), and sets made on whale sharks or baleen whales. However whale and whale shark associated sets are less frequent than the two first ones (∼ Capietto *et al.* 2014 Escalle *et al.* 2015). In addition, whale associated and free school sets, as well as whale shark and FAD sets, have been respectively found to present similar tuna Pallarés and Petit 1998) Therefore, considering that few sets are made on megafauna associated sets and due to the catch similarity with the main fishing modes, for management purposes, whale associated sets are commonly combined with free school sets and whale shark associated sets with FAD sets. Generally, composition and size of the targeted species catch is well known for the main fishing modes (FAD and free school sets), and have been Chassot *et al.* 2015b Delgado De Molina *et al.* 2015 Chassot *et al.* 2015a). Similarly, with the general adoption of an EAF approach and awareness of the importance of maintaining CDB 1992), assessment of bycatch species (i.e. non-target species or sizes incidentally captured) has been implemented through scientific onboard observer programs.

Generally, it has been identified that free school sets mostly capture large yellowfin tuna *Thunnus albacares*, while FAD sets capture mostly small tunas (skipjack *Katsuwonus pelamis*, as well as juveniles of yellowfin and bigeye tunas *Thunnus obesus*). Following an increasing use of FAD fishing in both the EAO and WIO since the 1990s, concerns have been Ariz *et al.* 1999 Hallier and Parajua 1999), as well as a potential modification of original behavior of tuna (i.e. Marsac *et al.* 2000 Hallier and Gaertner 2008). In addition, FAD sets also

capture much higher bycatch and of a higher number of species, including sensitive ones (i.e. silky shark *Carcharhinus falciformis* Kelleher 2005 Amandè *et al.* 2010 2012). To identify possible priority areas in terms of conservation, the spatio-temporal variability in the bycatch and its diversity has been investigated in both oceans, as well as Torres-Irineo *et al.* 2014 Lezama-Ochoa *et al.* 2015).

In contrast, for the two other fishing modes (whale and whale shark associated sets),

Romanov 2002) for targeted and bycatch species composition in 45 whale associated sets in the WIO). However, in spite of the relatively low occurrence of these fishing modes, this may currently be of importance. Indeed, there is a need for evidence of limited impacts of fishing practices on sensitive and emblematic encircled megafauna but also bycatches. This need has been accelerated recently, by the campaigns of certain NGOs against the extensive use of FAD, specifically because of the high biomass and diversity in the bycatch captured Greenpeace France 2014). Therefore, fishing companies may look for traceability of the tuna captured in order to promote tuna from free school sets or other fishing modes with lower ecological impacts than FAD sets. In this way, detailed knowledge of the species captured in association with whale sharks and baleen whales is specifically relevant. Furthermore, this also gives information concerning pelagic multi-specific catches and bycatches.

The pelagic associations between megafauna and other species remain difficult to study. Therefore access to open-ocean long-term fishery data may also increase knowledge on these associations. Baleen whales are considered to associate with tunas to feed on Hampton and Bailey 1999 Romanov 2002). On the other hand, whale sharks, due to their slow swimming in sub-surface behavior, are considered to aggregate several species, including tunas, but have also been recorded feeding altogether with tunas Hampton and Bailey 1999). In addition, whale sharks have been reported to associate with some other finfishes (e.g. species of trevally, bonito, mackerel or cobia *Rachycentron canadum*), as well as pilotfishes and sharksuckers and sometimes other shark species (e.g. scalloped hammerhead *Sphyrna lewini* and tiger *Galeocerdo cuvieri* sharks) or manta rays Colman 1997 Rowat and Brooks 2012). Nevertheless, data are still relatively scarce on the pelagic association between these filter feeder megafauna species and other animals.

In this context, the aims of this study were to i) assess composition and size of the targeted species, and ii) analyze bycatch diversity in whale and whale shark associated fishing sets in the EAO and WIO. In addition, a general comparison will be made with FAD and free school sets and among oceans to adequately characterize the species associated with these megafauna species and the difference with other species associations.

5.2 Material and methods

5.2.1 Data

Three data sources from the European tropical purse-seine fishery (France and Spain) were used in this study. Firstly, onboard scientific observer data over the 2003–2015 period were used to study the biodiversity and size spectrum of the bycatch. These data were collected by the IRD, the IEO and AZTI tecnalia as part of scientific observers programs conducted within EU data collection framework (EU DCF, regulation [CE] 199/2008). Observers programs represented an average coverage rate of ∼10% fishing sets per year over the 2003–2012 period and ∼70% over the 2014–2015. During a fishing set, onboard scientific observers recorded i) the date, hour and geographical position, ii) the cues, i.e. free swimming tuna schools or associated with floating objects, baleen whales, dolphins, whale sharks, flocks of birds, iii) the vessel captain estimation of the tuna catch by species and weight category, iv) the total bycatch (i.e. total number of individuals or total weight (tons, for most species weight was collected instead of number in less than 6% of the sets but for some abundant small fishes species it has been recorded in 5–26% of the sets, see Appendix 5.A), and mean size or mean weight) by species, if possible, or by large taxonomic level (gender, family, class, order), with the fate of each individual, v) precise measurements of a sample of the bycatch, included discarded tuna species (length, weight, sex for turtles, sharks and rays). The priority is given to vulnerable species (sharks, ray, turtles, billfishes), which are usually all sampled. For the rest of the bycatch (other bony fishes) at least 100–150 individuals were sampled. In addition, the maturity (i.e. juvenile or adult) of the individuals has been afterwards collected based on measurements of individuals sampled by observers and size-at-maturity for each species found in the literature.

Secondly, logbooks from the French (and associate flags) purse-seiners (collected by IRD) over the 1990–2015 period were compiled to compare the species composition and weight categories of tuna captured. Observers data were not used here because onboard observers report the captains' estimation, and logbook data included all fishing sets for a longer period of time. For each fishing set, vessel captains recorded in logbooks i) the date, hour and geographical position, ii) the possible associations (e.g. floating objects, baleen whales, whale sharks), and iii) the estimated tuna catch by species and weight category. The commercial weight categories were overlapping, they were thus redistributed following the logbook data correction procedure (see below). For instance, one of the original yellowfin and bigeye tunas category included individuals between 6 and 20kg, which was redistributed as follow: 20% in tuna < 10 kg and 80% in tuna ≥ 10 kg.

Thirdly, a last dataset, corresponding to measurements of the tuna catch taken by IRD at landing sites, was used to assess the size spectrum of the targeted species (i.e. yellowfin, skipjack and bigeye tunas). A multispecies sampling to estimate both size and species composition of the purse-seine catch has been implemented by IRD since the 1980s in the Cayré 1984 Pianet 1999). The sampling is made during the unloading of the purse-seiners at fishing ports and consists of a 2-step approach: (i) the brine-freezing wells are selected from among those containing homogeneous strata and (ii) a total in between 200–500 tunas are randomly collected, within size category, from the wells and counted Pallarés and Hallier 1997). Large fishes (>10 kg) are identified and measured in predorsal length to the nearest 0.5 cm Pallarés and Hallier 1997). Predorsal length measurements are then converted into fork length using species-specific keys of probability distribution to reflect individual variation). In the tuna sampled dataset, the catch from several fishing sets, made on different fishing modes, could be put in the same sampled well. Thus, only samples from wells containing the catch from one single fishing set or from several sets of the same fishing mode were selected here.

In this study, the fishing set was considered as the sample unit. For the three datasets, each fishing set was attributed a fishing mode, based on the cues recorded by scientific observers or vessel captains during the set (i.e. presence of whale sharks, baleen whales, dolphins, floating objects, flock of birds, presence of tuna detected visually or using the sonar). Therefore four fishing modes were identified: FAD sets (including natural logs and artificial objects), free school sets (FSC), whale associated sets (WHA) and whale shark associated sets (WHS). Any mixed set (i.e. presence of a whale shark and a floating object, whale and whale shark) was removed so it does not affect the species composition of each fishing mode. Dolphins sets were also not included in the analysis, due to their too low number (32 in the observer dataset in both oceans).

From the observer dataset, the initial list of all bycatch included 113 taxa identified at various taxonomic levels (species, genus, family, order and class). In order to analyse data from a list with the smallest taxonomic level possible (i.e. higher resolution), the taxa list from each large sub-region considered for spatial sampling were used to update the Pallarés and Hallier 1997 Escalle *et al.* 2016a). These are considered to be homogeneous in term of the species composition of tuna caught for each fishing mode (FAD Pallarés and Petit 1998). Then for each sub-region and fishing mode, higher taxonomic levels (33 taxa) were proportionally redistributed among the smaller taxonomic levels (80 taxa; mostly species, otherwise genus or family when no species was available) recorded in that sub-region and fishing mode. The whale shark and the cetacean's species,

which are directly related to the fishing mode and used to classify them, were not included in the taxa list.

5.2.2 Diversity analyses

Firstly, the total diversity by ocean and fishing mode, i.e. gamma diversity, was assessed using complementary methods. Regarding taxa richness, taxa accumulation curves Gotelli and Colwell 2001). Taxa accumulation curves were computed using randomized sampling without replacement in the dataset. For a given number of fishing sets, it gives the mean number of taxa caught with a 95% confidence interval. For the total number of fishing sets completed by fishing mode and ocean, it provides the total number of taxa caught. In addition, we computed the Chao 1987) which gives an estimation of the expected taxa richness present in the area that could be caught with the considered sampler, using extrapolation of taxa richness based on the occurrence of rare taxa. Then to accurately compare the number of taxa between fishing modes and ocean categories, we also computed the rarified number of taxa using a shared number of fishing sets (i.e. the smaller number of fishing sets by fishing modes and oceans). Regarding the relative dominance/evenness in abundance patterns of the Whittaker 1965) were computed by combinations of modalities in fishing mode and ocean. Each log rank-abundance curve was then fitted by Wilson 1991) to compare the structure of the taxa assemblages between fishing mode and ocean modalities. For each modality, the best model was assessed based on the lowest Bayesian's Information Etienne and Olff 2005). From the log rank-abundance curves, we selected the ten most abundant taxa for each fishing mode and ocean.

Secondly, the diversity of each fishing set, i.e. alpha diversity, was assessed through both taxa richness and evenness. For each fishing set, the number of individuals of all taxa N and the total number of taxa S, i.e. taxa richness, were calculated. Then we computed the potential inter-individual encounter *PIE* index, which represents the probability of having Hurlbert 1971). It accounts for both the number of taxa and the evenness. It is based on the Simpson diversity index $1-D$ Simpson 1949), which is calculated as follow: $1-D = 1-\sum_1^S p_i^2$ where $p_i = n/N$ (with n the abundance of the taxa i). PIE is the non biased Simpson diversity index: $PIE = \frac{N}{N-1}(1-D)$ Hurlbert 1971). Finally we calculated the Simpson Evenness E_{1-D} (Smith and Wilson 1996): $E_{1-D} = \frac{1-D}{1-1/S}$. In order to compare the indices (log(N), S, PIE and E_{1-D} between fishing modes and oceans, a non-parametric Kruskal-Wallis test was

performed. Then, if the null hypothesis of homogeneity in rank values distributions between fishing modes and oceans was rejected, a non parametric multi-comparison post-Hoc test Siegel and Castellan 1988) was computed to assess the pairwise differences between i) fishing modes in the same ocean and ii) each fishing mode among oceans.

Finally, the difference in the diversity in terms of both taxa abundance and composition between the fishing sets, i.e. beta diversity, was investigated according to the

Anderson and Willis 2003) was computed to provide a constrained ordination of samples (here fishing sets) to explicitly study the effect of a qualitative explanatory variable (crossed modalities of fishing mode and ocean) on taxa abundance and composition, from a distance matrix between samples (computed from square root of the Bray Curtis index). CAP integers into a Canonical Discriminant Analysis (CDA) the samples' coordinates on a subset of m axes, explaining a consequent part of data variation, resulting from a Principal Coordinate Analysis (PCoA, also known as metric Multi Dimensional Scaling, MDS). The canonical correlation was tested using 999 random permutations of the data. The difference in the taxa assemblage between fishing modes and oceans was assessed using a multivariate analysis of variance (MANOVA). To evaluate the distinction between groups (fishing mode and ocean) in the multivariate space, the CAP analysis provided a statistical estimate of misclassification using a "leave-one-out" approach. For each permutation, a single set was excluded from the analyses and afterwards classified in one of the group. The rates of allocation success (set correctly classified) or misclassification were then compiled by group. The species that contributed the most to each canonical axis were selected by having slight correlation $|r| \geq 0.1$ to that axis. The CAP analysis was then replicated accounting for the maturity of the individuals captured. Hence, each taxa has been devided into juvenile and adult groups and all these taxa/maturity categories were included in the analysis as variables.

All the statistical analyses and diversity indices were performed using R software (R Anderson 2002 Anderson and Willis 2003).

5.3 Results

A total of 7450 and 4738 fishing sets were sampled from the observer dataset in the 5.1). The large majority of these fishing sets were FADs and free schools (3228 (43.3%) and 3845 (51.6%) in the EAO, 2578 (54.4%) and 2027 (42.8%) in the WIO). There were 250 (3.0%) and 107 (2.3%) whale associated sets; and 127 (1.7%) and 24 (0.5%) whale shark associated sets, in the EAO and WIO, respectively. In the logbook

5.1). The majority was also FAD and free school, but there were 1245 (1.5%) and 5455 (5.9%) whale associated sets and 649 (0.8%) and 418 (0.5%) whale shark associated sets recorded in both oceans. The percentages of positive sets (at least one ton of tuna catch) by fishing mode and ocean were similar between the two datasets. For instance, in the observer dataset, free school sets had the lowest success rate (75 and 58% of positive sets in the EAO and WIO, respectively, see 5.1), followed by whale sets (80 and 69%), whale shark sets (95 and 60%) and FAD sets (93 and 94%). Similarly, few positive free school sets presented bycatch (39 and 24%), followed by whale sets (44 and 40%) and whale shark sets (54 and 42%). On the contrary, the majority of positive FAD sets also captured bycatch (88 and 93%).

Table 5.1 Main statistics of logbook and scientific observer datasets from the tropical tuna purse-seine fishery: tuna catch and bycatch diversity by fishing mode and ocean.

	Atlantic Ocean				Indian Ocean			
Fishing mode	**FAD**	**FSC**	**WHA**	**WHS**	**FAD**	**FSC**	**WHA**	**WHS**
Logbook dataset								
Total number of set	12 832	65 611	1245	649	46 621	40 004	5455	418
Number of positive set	12 414	54 47	916	507	42 782	21 954	3299	289
% positive set	96.7	83.0	73.6	78.1	91.8	54.9	60.5	69.1
Observer dataset								
Total number of taxa	68				68			
Total number of taxa - Chao2	71.6				80.2			
Number of fishing sets	3228	3845	250	127	2578	2027	109	24
Number of positive fishing sets	3010	2892	199	122	2427	1175	76	15
Number of sets with bycacth	2717	1284	109	69	2359	488	44	14
Number of positive set with bycatch	2657	1127	118	107	2327	379	38	14
% positive set	93.1	75.2	79.6	95.3	93.9	57.9	69.1	60.0
% sets with bycatch	84.2	33.4	43.6	54.3	91.5	24.1	40.4	58.0
% positive sets with bycatch	88.3	39.0	59.3	87.7	95.9	32.3	50.0	93.3
Total number of taxa	65	56	34	25	64	56	24	9
Total number of taxa - Chao2	68.5 ±3.5	60.5 ±4.8	50.3 ±11.6	35.0 ±9.0	73.0 ±10.2	61.3 ±4.9	36.0 ±9.6	13.0 ±4.7
Rarified number of taxa	20.8 ±2.4	8.5 ±1.7	9.6 ±1.7	11.3 ±1.6	24.4 ±2.8	7.9 ±2.2	9.7 ±1.7	9.0 ±1.4
Mean number of individuals per set	529.3 ±1200.3	36.2 ±120.1	23.8 ±38.5	22.8 ±54.1	414.1 ±1265.5	304.8 ±1695.3	10.0 ±13.1	13.3 ±16.6
Mean taxa richness per set	5.3 ±2.0	2.6 ±1.0	2.4 ±0.8	2.4 ±0.7	6.5 ±2.6	3.5 ±2.3	2.4 ±1.1	2.5 ±1.0
Mean PIE per set	0.5 ±0.2	0.6 ±0.3	0.5 ±0.3	0.7 ±0.3	0.7 ±0.2	0.8 ±0.2	0.9 ±0.2	0.7 ±0.2
Mean evenness per set	0.7 ±0.2	0.8 ±0.3	0.6 ±0.3	0.7 ±0.3	0.7 ±0.2	0.8 ±0.2	0.9 ±0.2	0.7 ±0.2
Mean tuna kept per positive set (t)	22.80 ±0.5	22.10 ±0.5	29.8 ±3.2	21.5 ±2.2	24.0 ±0.5	31.8 ±1.0	36.3 ±3.7	25.5 ±4.3
Mean tuna discard per positive set (t)	1.5 ±0.2	0.2 ±0.1	1.2 ±0.9	0.3 ±0.1	1.2 ±0.3	0.4 ±0.2	0.2 ±0.1	0.2 ±0.1
Mean bycatch per positive set (t)	0.6 ±0.0	0.1 ±0.0	0.6 ±0.1	0.4 ±0.3	0.8 ±0.0	0.3 ±0.2	0.2 ±0.1	0.3 ±0.2
% discard /tuna catch[1]	6.40 ±0.3	0.70 ±0.1	1.90 ±0.9	3.10 ±1.2	6.90 ±0.4	1.70 ±0.3	0.40 ±0.2	0.90 ±0.4
% bycatch & discard/total catch[2]	11.1 ±0.4	1.5 ±0.1	4.0 ±1.2	4.1 ±1.3	12.1 ±0.4	2.6 ±0.4	1.4 ±0.4	2.0 ±0.6
% bycatch /total catch[2]	5.1 ±0.2	1.0 ±0.7	2.6 ±1.9	1.0 ±0.4	6.8 ±0.3	1.2 ±0.2	1.0 ±0.4	1.0 ±0.5

Diversity indices, tuna catch and bycatch are given as mean ± standart error.

[1] Percentage of tuna discarded over the total tuna catch (kept and discarded)

[2] Percentage of bycatch and tuna discarded or bycatch only over the total catch and bycatch (tuna kept and discarded and bycatch)

5.3.1 Tuna catch

The average total tuna catch per positive set was higher, for all fishing modes, in the 5.2, Kruskal Wallis tests, $Chi^2=15048.1$, d.f.=7, $p<2.2e^{-16}$ and

multiple comparisons tests $p<0.05$). In addition, whale associated sets presented the highest average tuna catch per positive set in both oceans (28.6 t ±1.1 and 37.8 t ±0.7 in the EAO and WIO, respectively). Then free school (18.8 t ± 0.8 and 35.2 t ±0.3), FAD (19.2 t ±0.2 and 30.6 t ±0.2) and whale shark associated sets (18.2 t ±0.1 and 25.1 t ±1.6) had a lower average total catch. It should however be mentioned, again, that FAD sets always presented the highest percentage of positive sets (96.7 and 91.8% in the EAO and WIO, respectively).

Table 5.2 Mean catch per set by fishing mode and ocean from the logbook dataset.

Ocean - Fishing mode	Total catch (t)	YFT (t)	SKJ (t)	BET (t)	ALB (t)	FRI (t)	LTA (t)	Other (t)
EAO - FAD	19.2 ± 0.2	2.9 ± 0.1	14.0 ± 0.2	1.6 ± 0.04	0.0 ± 0.0	0.02 ± 0.0	0.04 ± 0.01	0.7 ± 0.05
WIO - FAD	30.6 ± 0.2	4.8 ± 0.1	21.5 ± 0.1	1.1 ± 0.02	0.01 ± 0.01	0.0 ± 0.0	0.0 ± 0.0	3.2 ± 0.07
EAO - FSC	18.2 ± 0.1	10.6 ± 0.1	6.2 ± 0.1	1.0 ± 0.02	0.05 ± 0.01	0.01 ± 0.0	0.01 ± 0.0	0.3 ± 0.02
WIO - FSC	35.2 ± 0.3	26.2 ± 0.3	6.1 ± 0.1	0.9 ± 0.04	0.44 ± 0.02	0.0 ± 0.0	0.0 ± 0.0	1.5 ± 0.06
EAO - WHA	28.6 ± 1.1	18.6 ± 0.9	8.2 ± 0.7	1.3 ± 0.2	0.03 ± 0.01	0.0 ± 0.0	0.0 ± 0.0	0.5 ± 0.2
WIO - WHA	37.8 ± 0.7	26.5 ± 0.6	8.3 ± 0.4	1.1 ± 0.1	0.38 ± 0.04	0.0 ± 0.0	0.0 ± 0.0	1.5 ± 0.2
EAO - WHS	18.8 ± 0.8	5.9 ± 0.4	11.6 ± 0.6	1.1 ± 0.2	0.03 ± 0.02	0.0 ± 0.0	0.0 ± 0.0	0.2 ± 0.2
WIO - WHS	25.1 ± 1.6	10.4 ± 1.3	11.2 ± 0.8	2.1 ± 0.7	0.07 ± 0.04	0.0 ± 0.0	0.0 ± 0.0	1.4 ± 0.3

EAO: eastern Atlantic Ocean, WIO: western Indian Ocean. YFT= yellowfin, SKJ= skipjack, BET= bigeye, ALB= albacore, FRI= frigate tuna, LTA= little tuna and other minor tuna species. FAD: Fish Aggegating Device set, FSC: free school set, WHA: whale associated set, and WHS: whale shark associated set.

Concerning the average catch per species, significant difference between oceans 5.2, Kruskal Wallis tests, $Chi^2>3795.2$, d.f.=7, $p<2.2e^{-16}$ and multiple comparisons tests $p<0.05$) was found for most species and fishing modes. The catch of skipjack and bigeye was however the same for whale and whale shark associated sets between oceans, as 5.2, multiple comparisons tests).

5.3) were composed of mixed species (i.e. multi-specific catch, mostly skipjack, yellowfin and bigeye tunas). In contrast, 5.3) were composed of only one species (mono-specific catch). In the case of mono-specific catch, FAD mainly presented sets with skipjack (34 and 39% of the sets) and to a lesser extent with only yellowfin or bigeye (<8 and <4% of the sets). Likewise, whale shark mono-specific sets were mostly made on skipjack (29 and 34%), but also yellowfin (16 and 22%). Free school and whale associated mono-specific sets were mostly composed of yellowfin (34 and 59% for free school sets, and 54 and 56% for whale sets), as well as of skipjack (26 and 17%; 18 and 13%), but

very few of bigeye (<4%).

In terms of tonnage captured, as mentioned, whale associated sets presented the highest tuna catch with mostly large yellowfin, followed by free school sets in the WIO (large yellowfin) and FAD sets in the EAO (skipjack). Indeed, on whale associated sets, the catch was of 18.6 t of large and medium yellowfin in the EAO and 26.5 t in the WIO, 6 t of 5.2 5.1). Similarly, the average catch by species on free school sets was of 10.6 t (EAO) and 26.2 t (WIO) of large and medium yellowfin, 6 t of skipjack and 1.1 t of large bigeye. On FAD sets, the average catch per species was 14.0 t (EAO) and 21.5 t (WIO) of skipjack, 2.9 and 4.8 t of yellowfin (all sizes) and ∼1.3 t of small bigeye. Likewise, the average catch per species on whale shark associated sets was of 11.6 t (EAO) and 11.2 t (WIO) of skipjack, 5.9 and 10.4 t of mostly medium and large yellowfin and ∼1.5 t of large bigeye.

Table 5.3 Percentage of multi and mono-specific sets by fishing mode and ocean obtained from the logbook dataset.

Ocean	Fishing mode	Multi-specific catch	Mono-specific catch			
			SKJ	YFT	BET	Other species
EAO	FAD	50.8	34.1	8.3	4.1	2.7
WIO	FAD	46.2	38.7	4.7	0.2	10.2
EAO	FSC	32.9	26.1	35.6	4.1	1.4
WIO	FSC	17.7	17.3	58.8	0.4	5.9
EAO	WHA	23.9	18.1	54.1	2.9	0.9
WIO	WHA	24.8	12.9	55.8	0.5	6.0
EAO	WHS	53.6	29.0	15.6	1.2	0.6
WIO	WHS	37.0	33.6	21.5	0.0	8.0

EAO: eastern Atlantic Ocean, WIO: western Indian Ocean. YFT= yellowfin tuna, SKJ= skipjack tuna, BET= bigeye tuna. FAD: Fish Aggegating Device set, FSC: free school set, WHA: whale associated set, and WHS: whale shark associated set.

Finally, concerning the size spectrum of major tuna captured, it was generally different by fishing mode between oceans for yellowfin and skipjack, but was the same 5.2). In both oceans, the size spectrum of the three major tuna species captured on FAD and on whale shark associated sets were however different (except for skipjack in the EAO). This is due to the capture of large yellowfin and bigeye tunas (>120 cm) on whale shark sets, which only slightly appear in 5.2). In contrast, in both oceans, the size spectrum of each tuna species were the same between free school and whale associated sets (Kolmogrov-Smirnov test 0.74<p-value<1.00). For the rest of the fishing modes, the size spectrum of yellowfin and bigeye tunas were mostly different (except between free school and whale shark and whale and whale shark for bigeye tuna in the EAO). For skipjack, the size spectrum was

mostly the same among fishing modes, as this species is mostly captured between 30 and 70 cm for all fishing modes.

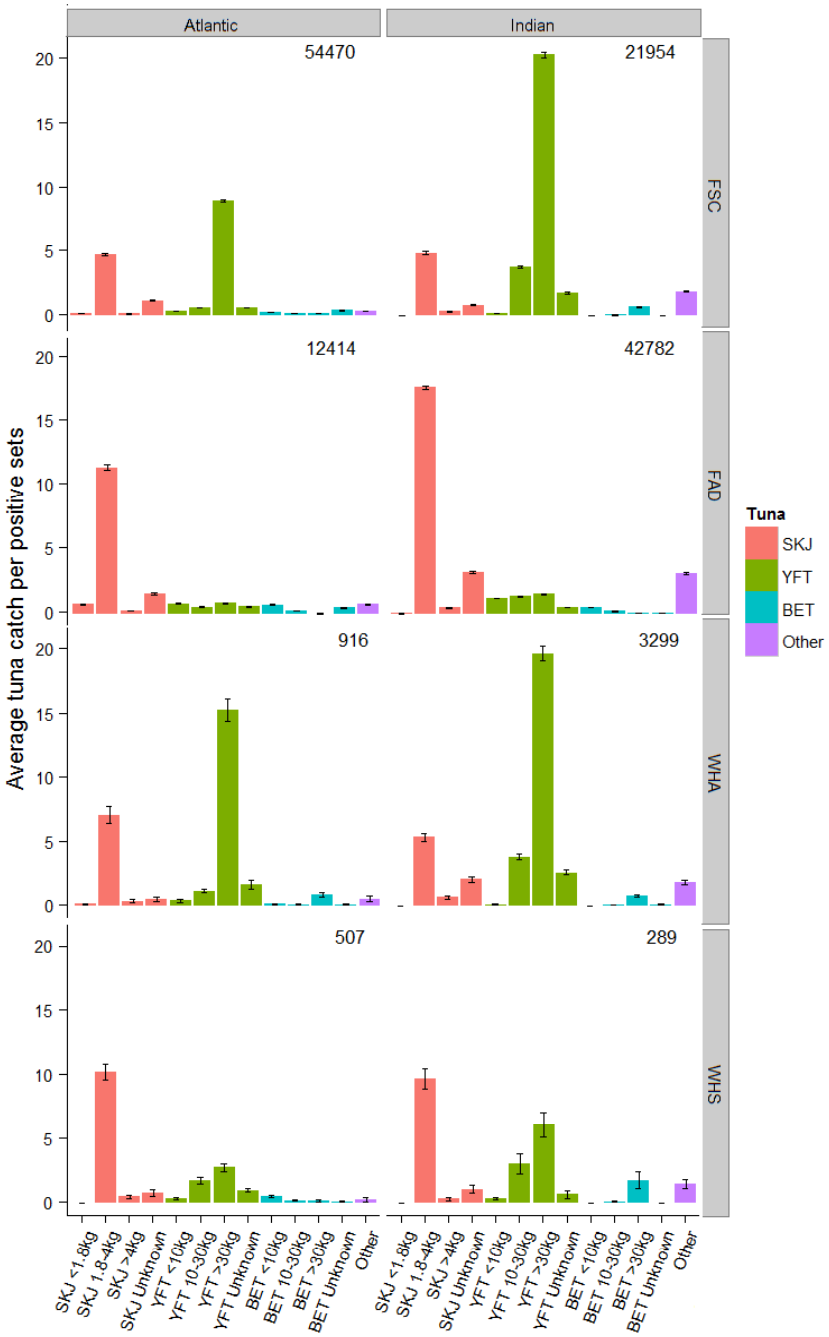


Figure 5.1 Mean tuna catch by species (in tons) and weight category by fishing mode recorded in logbooks over the 1990–2015 period. YFT= yellowfin tuna, SKJ= skipjack tuna, BET= bigeye tuna, Other = albacore and other minor tuna species, FAD= Fish Aggregating Device set, FSC= free school set, WHA= whale associated set, WHS= whale shark associated set.

5.3.2 Bycatch diversity

From the 4179 (56%) and 2905 (61%) fishing sets with bycatch sampled in the EAO 5.1). Almost all taxa were recorded in FAD sets (65 and 64 taxa). In both oceans, 56 taxa were recorded in free

school sets. Finally 34 and 24 were recorded in whale sets, and 25 and 9 were recorded in whale shark sets, for the EAO and WIO, respectively (keeping in mind that number of sets are different among oceans and fishing modes, see below for rarified values comparison). None 5.3) as it is usually the case in ecological studies, due to the large number of rare species present in natural communities. However, the slope at the end of the curves of FAD and free school sets suggested that the number of additional sets necessary to collect more exhaustively the species with the fishing modes used should only be slightly higher. Conversely, whale and whale shark sets clearly need more samples, compared to FAD and free school sets that are closer to the asymptote. Complementarily, the Chao2 index estimated that the total number of taxa that could be encircled in the EAO and WIO, respectively, is of i) 68.5 ±3.5 and 73.0 ±10.2 in FAD sets, ii) 60.5 ±4.8 and 61.3 ±4.9 in free school sets, iii) 50.3 ±11.6 and 36.0 ±9.6 in whale associated sets, and iv) 35.0 ±9.0 and 13.0 ±4.7 in whale shark associated sets. In addition, when considering the same number of fishing sets among fishing modes and oceans (i.e. 24 sets), the rarified number of taxa allow direct and accurate comparison. It was thus found that FAD sets presented a higher number of taxa (20.8 ±2.4 and 24.4 ±2.8) than the three other fishing modes (8.5 ±1.7, 9.6 ±1.7 and 11.3 ±1.6 for free school, whale and whale shark sets in the EAO; 7.9 ±2.2, 9.7 ±1.7 and 9.0 ±1.4 in the WIO).

The ten most abundant taxa represented more than 88.2% (up to 100% for whale sharks sets in the WIO) of the total number of individuals captured by fishing mode and 5.4). Besides species that were only found in one ocean (i.e. *Caranx crysos*, *Balistes carolinensis*, *Balistes punctatus*, *Kyphosus sectatrix* only present in the EAO; *Abalistes stellaris*, *Kyphosus cinerascens* and *Kyphosus vaigiensis* only in the WIO), the most abundant taxa were relatively similar between FAD and free school sets and between oceans. For instance *Canthidermis maculata*, *Elagatis bipinnulata*, *Coryphaena hippurus* were among the ten most abundant taxa captured in these two fishing modes and oceans. However, some differences between these fishing modes could also be distinguished. *Kyphosus spp.* were only among the ten most abundant taxa in FAD sets, while *Istiophorus albicans*, *Lobotes surinamensis*, *Diodon hystrix* and *Aluterus monoceros* only in free school sets. On the other hand, the ten most abundant taxa on whale and whale shark sets were relatively different than the ones on FAD and free school sets. *Carcharhinus falciformis* was systematically the most adundant taxa on these fishing modes.

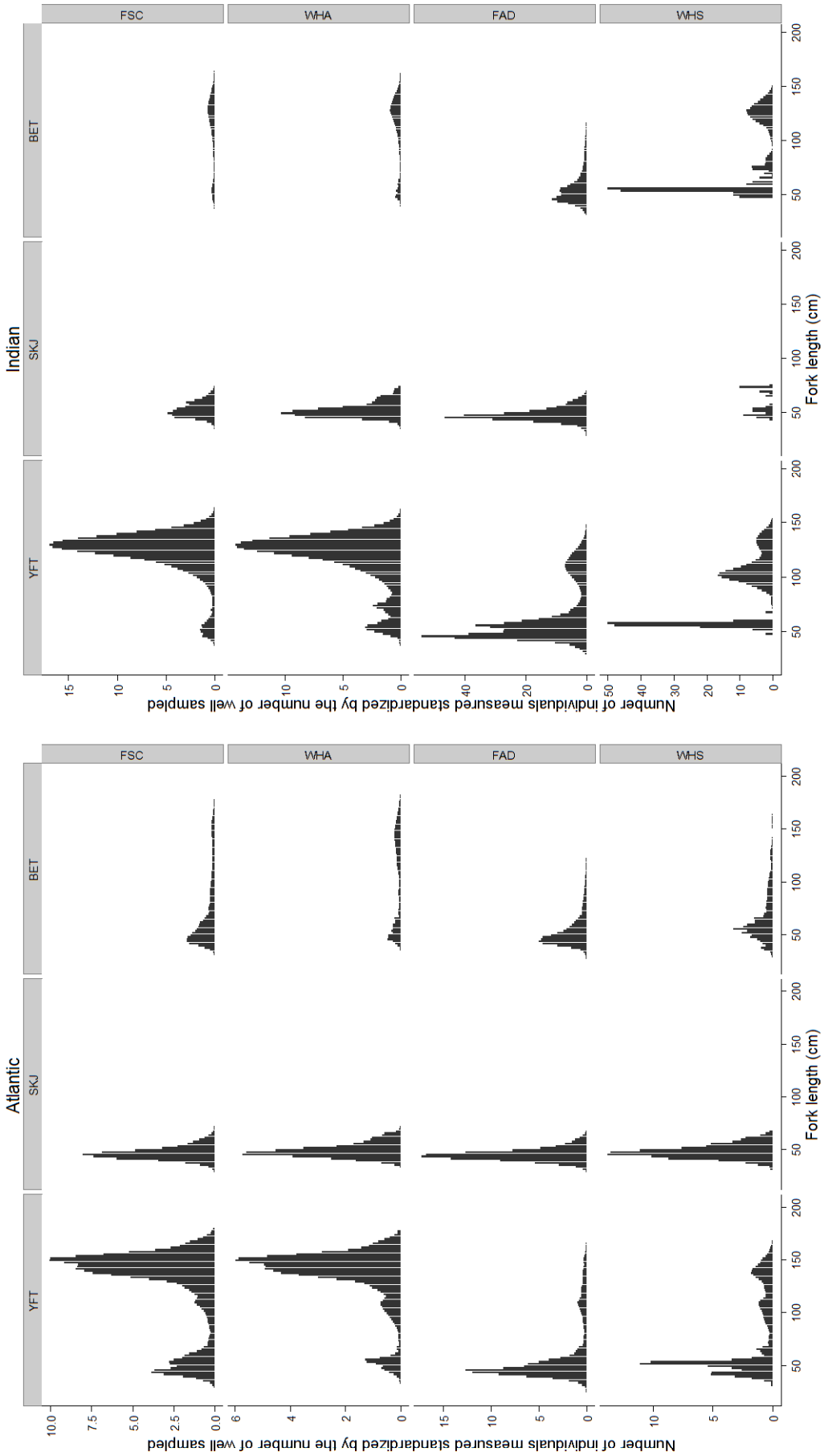


Figure 5.2 Size spectrum of the major tuna species captured by fishing mode and ocean, based on the sampled taken at landing sites. YFT= yellowfin tuna, SKJ= skipjack tuna, BET= bigeye tuna, FAD= Fish Aggregating Device set, FSC= free school set, WHA= whale associated set, WHS= whale shark associated set.

However, it should be noted that while the occurrence of *C. falciformis* in whale and whale shark associated sets (∼15%) is lower than on FAD (70%) in the WIO, when the species is present the number of individuals per set was similar (∼ 5.1). In contrast, in the EAO, occurrence was similar for whale and FAD sets (∼25%), but the number of individuals per set was higher in whale associated sets (24 ±5.8) than in the other fishing 5.1).

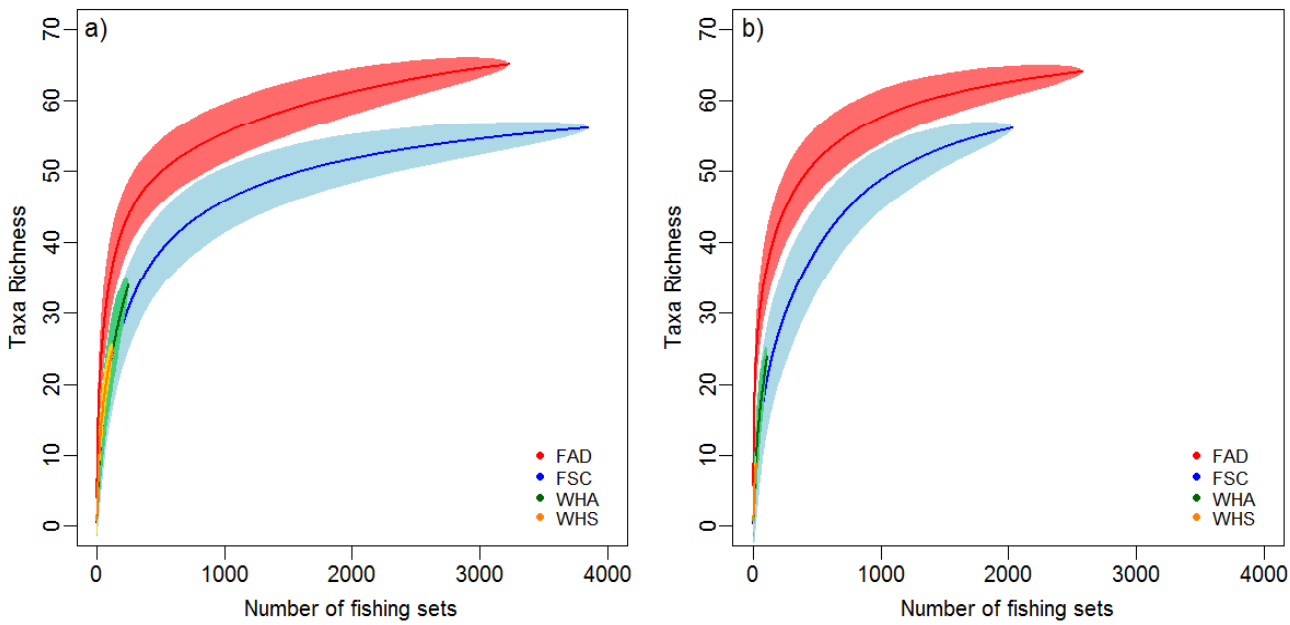


Figure 5.3 Taxa accumulation curves per fishing mode in a) the Atlantic Ocean, and b) the Indian Ocean. FAD= Fish Aggregating Device set, FSC= free school set, WHA= whale associated set, WHS= whale shark associated set.

In addition, in whale and whale shark sets, other sharks and rays (i.e. *Prionace glauca*, *Dasyatys violacea* and *Mobula japonica*), billfishes (*Makaira nigricans*, *I. albicans*, *Makaira indica* and *Istiophorus platypterus*), Porcupinefishes and/or Pufferfishes (*Diodon hystrix* and *Lagocephalus lagocephalus*), as well as some pilot fishes for whale shark sets (*Echeneis naucrates*, *Remora remora*) appeared among the ten most abundant taxa. Finally, some taxa previously mentioned in FAD and free school sets were also among the most abundant taxa in whale sets (*C. maculata*, *C. crysos*, *E. bipinnulata* and *A. stellaris*) or in both whale and whale shark sets (*C. hippurus*).

Table 5.4 Abundance (N), mean number per set when present and proportion of individuals for the ten most abundant taxa by fishing mode and ocean.

		Atlantic Ocean						Indian Ocean					
	Rank	Taxa	N	Nb/set	Prop.[1] (%)	Cumulative Prop. (%)	Log(N)	Taxa	N	Nb/set	Prop. (%)	Cumulative Prop. (%)	Log(N)
FAD	**1**	*Caranx crysos*	644695	365	46.7	46.7	5.8	*Canthidermis maculata*	496870	281	52.5	52.5	5.7
	2	*Canthidermis maculata*	403104	215	29.2	75.9	5.6	*Elagatis bipinnulata*	208607	115	22	74.5	5.3
	3	*Elagatis bipinnulata*	191689	102	13.9	89.8	5.3	*Coryphaena hippurus*	67481	37	7.1	81.7	4.8
	4	*Seriola rivoliana*	28265	70	2	91.9	4.5	*Decapterus macarellus*	30848	53	3.3	84.9	4.5
	5	*Coryphaena hippurus*	21983	13	1.6	93.5	4.3	*Abalistes stellaris*	29456	152	3.1	88	4.5
	6	*Balistes carolinensis*	19286	52	1.4	94.9	4.3	*Acanthocybium solandri*	23140	21	2.4	90.5	4.4
	7	*Acanthocybium solandri*	18041	136	1.3	96.2	4.3	*Carcharhinus falciformis*	15954	9	1.7	92.2	4.2
	8	*Uraspis secunda*	13209	136	1	97.1	4.1	*Uraspis secunda*	11978	21	1.3	93.4	4.1
	9	*Balistes punctatus*	9193	203	0.7	97.8	4	*Kyphosus cinerascens*	10112	26	1.1	94.5	4
	10	*Kyphosus sectatrix*	7562	24	0.5	98.3	3.9	*Kyphosus vaigiensis*	8545	29	0.9	95.4	3.9
FSC	**1**	*Canthidermis maculata*	7239	79	37.3	37.3	3.9	*Canthidermis maculata*	22007	488	45.9	45.9	4.3
	2	*Elagatis bipinnulata*	2433	24	12.5	49.8	3.4	*Elagatis bipinnulata*	17917	397	37.3	83.2	4.3
	3	*Istiophorus albicans*	1912	4	9.8	59.6	3.3	*Abalistes stellaris*	2082	1034	4.3	87.5	3.3
	4	*Carcharhinus falciformis*	1637	8	8.4	68	3.2	*Coryphaena hippurus*	1566	26	3.3	90.8	3.2
	5	*Caranx crysos*	1551	62	8	76	3.2	*Decapterus macarellus*	1088	208	2.3	93	3
	6	*Lobotes surinamensis*	1147	25	5.9	81.9	3.1	*Acanthocybium solandri*	855	25	1.8	94.8	2.9
	7	*Coryphaena hippurus*	851	7	4.4	86.3	2.9	*Carcharhinus falciformis*	699	7	1.5	96.3	2.8
	8	*Balistes carolinensis*	631	57	3.2	89.6	2.8	*Uraspis secunda*	394	25	0.8	97.1	2.6
	9	*Diodon hystrix*	440	7	2.3	91.8	2.6	*Lobotes surinamensis*	268	11	0.6	97.7	2.4
	10	*Seriola rivoliana*	218	73	1.1	92.9	2.3	*Aluterus monoceros*	214	21	0.4	98.1	2.3
WHA	**1**	*Carcharhinus falciformis*	1115	24	59.7	59.7	3	*Carcharhinus falciformis*	101	9	44.3	44.3	2
	2	*Diodon hystrix*	319	53	17.1	76.8	2.5	*Abalistes stellaris*	20	20	8.8	53.1	1.3
	3	*Lagocephalus lagocephalus*	150	150	8	84.8	2.2	*Coryphaena hippurus*	18	5	7.9	61	1.3
	4	*Istiophorus albicans*	63	4	3.4	88.2	1.8	*Dasyatys violacea*	17	3	7.5	68.4	1.2
	5	*Canthidermis maculata*	30	7,5	1.6	89.8	1.5	*Canthidermis maculata*	10	10	4.4	72.8	1
	6	*Caranx crysos*	30	30	1.6	91.4	1.5	*Makaira nigricans*	8	1	3.5	76.3	0.9
	7	*Prionace glauca*	25	1	1.3	92.7	1.4	*Lagocephalus lagocephalus*	8	8	3.5	79.8	0.9
	8	*Mola mola*	17	1	0.9	93.6	1.2	*Makaira indica*	7	1	3.1	82.9	0.8
	9	*Elagatis bipinnulata*	16	8	0.9	94.5	1.2	*Sphyraena barracuda*	7	2	3.1	86	0.8
	10	*Makaira nigricans*	14	1,3	0.7	95.2	1.1	*Istiophorus platypterus*	5	3	2.2	88.2	0.7
WHS	**1**	*Carcharhinus falciformis*	319	32	37.3	37.3	2.5	*Carcharhinus falciformis*	28	14	43.1	43.1	1.4
	2	*Lagocephalus lagocephalus*	233	28	27.3	64.6	2.4	*Remora remora*	24	5	36.9	80	1.4
	3	*Echeneis naucrates*	95	5	11.1	75.7	2	*Ablennes hians*	5	5	7.7	87.7	0.7
	4	*Remora remora*	58	6	6.8	82.5	1.8	*Makaira indica*	2	1	3.1	90.8	0.3
	5	*Coryphaena equiselis*	50	50	5.8	88.3	1.7	*Coryphaena hippurus*	2	1	3.1	93.8	0.3
	6	*Coryphaena hippurus*	19	3	2.2	90.5	1.3	*Makaira nigricans*	1	1	1.5	95.4	0
	7	*Makaira nigricans*	17	2	2	92.5	1.2	*Dasyatys violacea*	1	1	1.5	96.9	0
	8	*Naucrates ductor*	14	2	1.6	94.2	1.1	*Xiphias gladius*	1	1	1.5	98.5	0
	9	*Prionace glauca*	8	1	0.9	95.1	0.9	*Acanthocybium solandri*	1	1	1.5	100	0
	10	*Mobula japanica*	7	2	0.8	95.9	0.8						

FAD: Fish Aggegating Device set, FSC: free school set, WHA: whale associated set, and WHS: whale shark associated set.
[1]Proportion of individuals for the related taxa among the total number of individuals.
[2]P

The dominance/evenness profile mainly differed between fishing modes, but was 5.4).

Indeed the taxa abundance models selected according to the BIC criterion showed different taxa assemblages between fishing modes. In particular the profile of the taxa assemblage that could be attributed to whale sets (Zipf model) was different to whale shark sets (Mandelbrot model) or to FAD and free school sets (log-normal model, except free school in the EAO: Mandelbrot model).

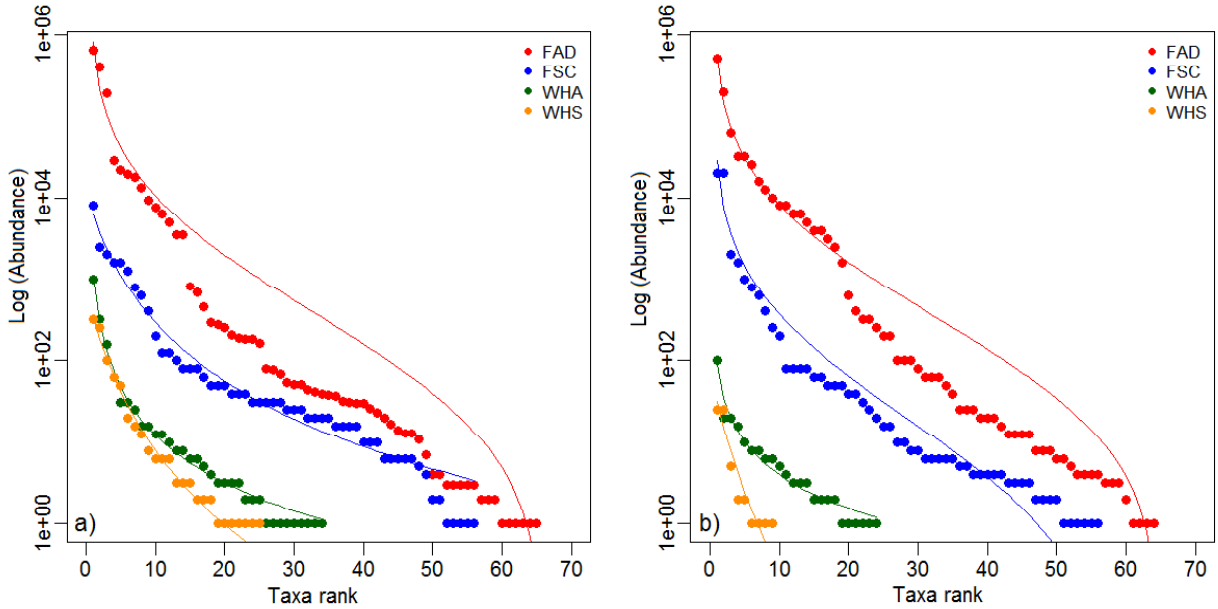


Figure 5.4 Taxa rank log (abundance) curve for each fishing mode in a) the Atlantic Ocean, and b) the Indian Ocean. FAD= Fish Aggregating Device set, FSC= free school set, WHA= whale associated set, WHS= whale shark associated set.

Abundance and diversity indices were also different between fishing mode and ocean 5.5, Kruskal Wallis tests, 94.4<Chi2<1074.9, d.f.=7, $p<2.2e^{-16}$).

In particular, multiple comparisons tests ($p<0.05$) showed that abundance and taxa richness were higher in FAD sets (529.3 and 414.1 individuals, and 5.3 and 6.5 taxa per set in the EAO and WIO, respectively) than in the three other fishing modes by ocean (10.0–304.8 individuals and 2.4–3.5 taxa). Abundance and taxa richness were also higher in the WIO than in the EAO for FAD and free school sets. PIE only significantly differed, with relatively high values, between FAD and free school, among and between oceans (0.5 and 0.6 for FAD in the EAO and WIO and 0.7 and 0.8 for free school). Finally the Simpson evenness was different between oceans for whale sets (0.6 in the EAO and 0.9 in the WIO), as well as between FAD (0.7) and free school (0.8) in both oceans, and between FAD (0.7) and whale sets (0.9) in the WIO.

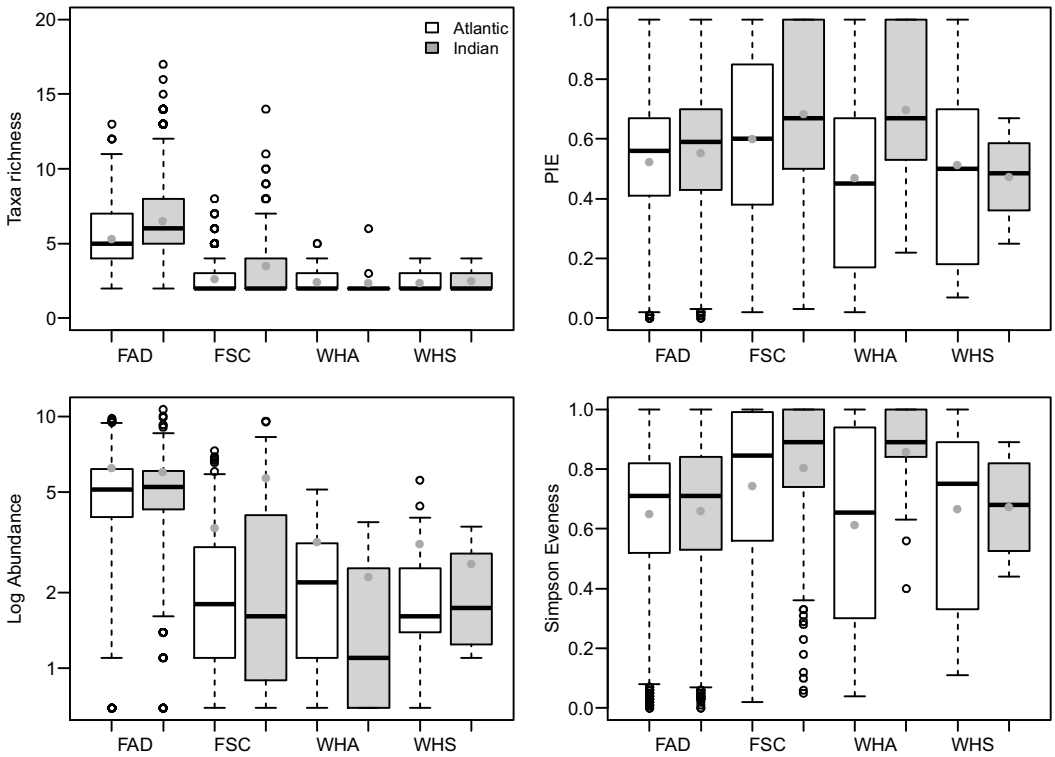


Figure 5.5 Boxplot of the taxa richness, potential inter-individual encounter (PIE), log (abundance) and Simpson's evenness per set.

The Canonical Analysis of Principal Coordinates (CAP) showed a significant effect 5.6 5.5) on species composition and abundance of assemblages, with a squared canonical correlation of δ^2 = 0.69 (p = 0.001) (similar results when found when maturity stages were accounted for, see Appendix 5.B). While the crossed categories of fishing mode and ocean were investigated 5.6 that the 1st canonical axis corresponds to the fishing mode and the 2nd to the ocean. The taxa assemblage captured on FAD sets was clearly 5.6). In addition, a distinction can also be made on FAD sets between oceans, as well as slightly on free school sets. The distinctiveness of the taxa assemblage captured on each fishing mode is also confirmed by 5.5). Indeed the taxa assemblage on FAD sets was successfully allocated in 79 and 88% of the cases in the EAO and WIO, respectively. For free school, the allocation success was of 59 and 51 %. It was however lower for whale (32 and 0 % in the EAO and WIO) and whale shark (11.6 and 0 %). In case of misclassification FAD sets from one ocean were mostly classified as FAD sets from the other ocean (14.8 and 7.2%). For free school sets, it was either the same (13 and 9%), or they were classified as FAD sets from the same ocean (11.5 and 6.8%), as whale sets in the EAO (10%) or as whale shark sets in the WIO (11%). Finally, misclassified whale and whale

shark sets were mostly considered as free school sets from the same ocean (42 and 50% for whale sets and 49 and 40% for whale shark sets).

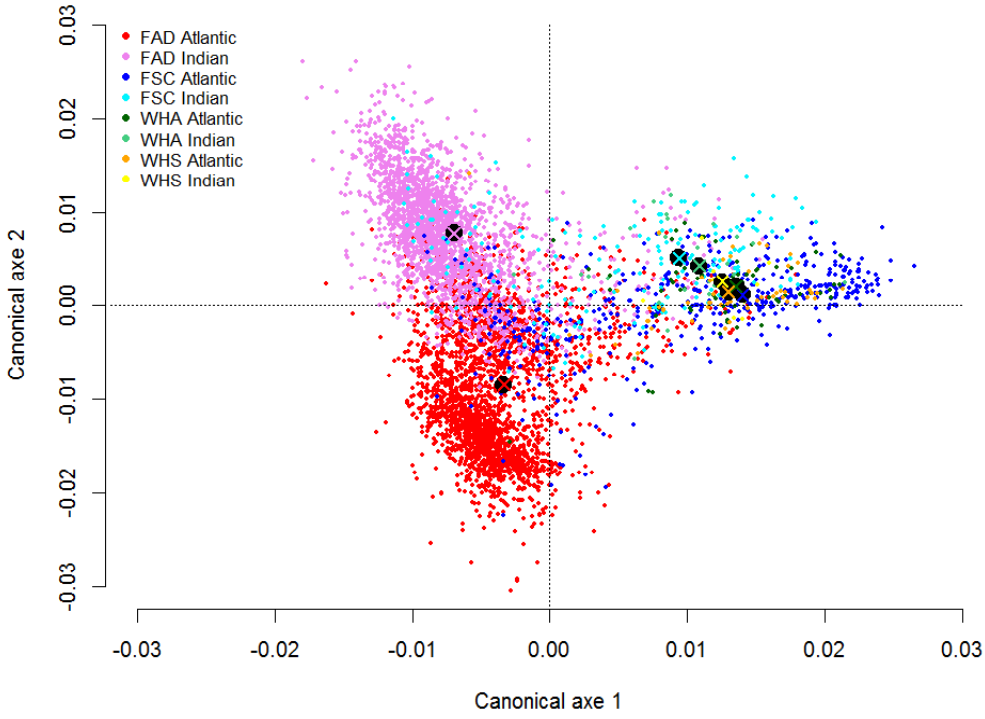


Figure 5.6 Two dimensional scatter plot of the axes of the Canonical Analysis of Principal Coordinates (CAP). Crosses represent the barycentres of each modality. FAD= Fish Aggregating Device set, FSC= free school set, WHA= whale associated set, WHS= whale shark associated set.

Taxa slightly negatively correlated with the canonical axis fishing mode (axis 1) were *C. hippurus* (r= -0.3), *Acanthocybium solandri*, *Sphyraena barracuda*, *C. maculata* and *C. falciformis* 5.6). The taxa slightly positively correlated with this axis were *I. albicans*, *P. glauca* and *M. japonica*, mostly found in free school, whale and whale shark sets. Likewise, the taxa slightly correlated with the canonical axis ocean (axis 2) were taxa with higher abundance in the set in one ocean (i.e. *C. falciformis*, *C. hippurus*, *K. cinerascens*, *M. indica* or *C. equiselis* in the WIO and *M. nigricans* in the EAO) or taxa only present in one ocean (i.e. *C. crysos* or *B. carolinensis* in the EAO).

Table 5.5 Results of Canonical Analysis of Principal Coordinates (CAP) examining the effects of the cross modalities of fishing mode and ocean.

		Allocation success %								Manova p-value	m	% Var	δ^2	P
Explanatory variable		FAD EAO	FAD WIO	FSC EAO	FSC WIO	WHA EAO	WHA WIO	WHS EAO	WHS WIO					
		79.2	87.7	58.6	50.6	32.1	0	11.6	0	$< 2.0e^{-16}$	46	98.4	0.69	0.001
% **allocation**					Predicted									
Originals	FAD EAO	79.2	14.8	3.1	1.2	0.7	0.3	0.1	0.6					
	FAD WIO	7.2	87.7	1.5	1.8	1.1	0.3	0.08	0.3					
	FSC EAO	10	3.3	58.6	12.9	10	0.7	3	1.2					
	FSC WIO	6.8	11.5	8.6	50.6	3.3	4.3	4.5	10.5					
	WHA EAO	2.8	1.8	42.2	16.5	32.1	1.8	0.9	1.8					
	WHA WIO	2.3	6.8	9.1	50	9.1	0	13.6	9.1					
	WHS EAO	4.3	1.4	47.8	13	14.5	2.9	11.6	4.3					
	WHS WIO	10	10	30	40	10	0	0	0					

Allocation success = percentage of points correctly allocated into each group, %Var = percentage of the total variation explained by the first m principal coordinate axes, δ^2 = squared canonical correlation, and P = associated probability.
EAO: eastern Atlantic Ocean, WIO: western Indian Ocean. FAD: Fish Aggegating Device set, FSC: free school set, WHA: whale associated set, and WHS: whale shark associated set.

5.4 Discussion

Within an EAF framework, in addition to assessing the catch of targeted species, it has now also been considered necessary to evaluate the biomass and diversity of bycatch captured by fisheries using certain fishing modes. In the EAO and WIO, these two aspects are relatively well studied for the two main fishing modes (FAD and free school sets) used Fonteneau *et al.* 2013 Torres-Irineo *et al.* 2014 Lezama-Ochoa *et al.* 2015). On the other hand, setting on the two other fishing modes, i.e. tuna schools associated with baleen whales or whale sharks, are less studied. This may be due to the fact that they are less frequent and mostly concentrated in specific spatio-temporal Capietto *et al.* 2014 Escalle *et al.* 2015). The catch and bycatch on these fishing modes have therefore yet to be better studied. To fill this gap, we have used scientific onboard observer data, skippers' logbook and sampling at landing site data. It should be kept in mind that in the estimates of tuna captured by fishing mode, we have used the logbook uncorrected dataset. Therefore the capture of juvenile bigeye tuna may be confused with

juvenile yellowfin tuna (more common). This is however not the case in the samples taken at landing sites, which was then complementary used to present the size spectrum by species 5.2). Nevertheless, it should be noted that samples used in this study corresponds mostly to large tonnage fishing sets (wells containing only the catch from a specific fishing mode, i.e. mostly from one fishing set). Therefore a bias due the presence of only large sets and no smaller ones might not be excluded. Likewise, in these samples, as well as the logbook data, there is a lack of very small (i.e. juveniles skipjack) or small tunas that are often discarded. These are however assessed by observers as part of the catch that is discarded. Nevertheless, the coverage rate of observers was historically low (∼10% before 2014). Thus, each of the three databases used presented some limitations, which justifies their complementary use.

Table 5.6 Correlation coefficients for individual taxa ($|r| \geq 0.10$) with the canonical axes 1 and 2 of the Canonical Analysis of Principal Coordinates (CAP). Taxa are ranked by absolute value of correlation coefficient.

Taxa	**Axis 1**	**Taxa**	**Axis 2**
Coryphaena hippurus	-0.30	*Carcharhinus falciformis*	0.28
Acanthocybium solandri	-0.26	*Coryphaena hippurus*	0.25
Istiophorus albicans	0.26	*Caranx crysos*	-0.24
Sphyraena barracuda	-0.17	*Kyphosus cinerascens*	0.14
Canthidermis maculata	-0.16	*Makaira indica*	0.13
Carcharhinus falciformis	-0.15	*Makaira nigricans*	-0.13
Prionace glauca	0.12	*Coryphaena equiselis*	0.11
Mobula japonica	0.10	*Balistes carolinensis*	-0.10

Regarding the main results of this study, firstly concerning tuna catch, whale associated sets resulted in the highest average tuna catch per positive set. Whale shark associated sets, on the other hand, presented the lowest average tuna catch per set. In addition, whale associated sets caught tuna species and size categories similar to free school sets. The majority of these sets were made on mono-specific schools of large yellowfin tuna. Likewise, whale shark associated and FAD sets presented similar pattern of tuna catch with some slight differences. Both fishing modes often caught mixed schools of mainly skipjack, yellowfin and bigeye tunas. However, while yellowfin and bigeye tunas were mostly juveniles (<10kg) in FAD sets, more large individuals (>30kg) were found in whale shark associated sets. Nevertheless, the fact that whale sharks and free schools (large yellowfin) co-occured in space but did not directly associate, may not be excluded. Secondly, concerning bycatch, FAD sets presented higher mean abundance and taxa richness per set than the three other fishing modes. The structure of the taxa assemblage, and the most abundant taxa, were similar between FAD and free school sets, but differed with whale and whale shark sets.

However, beta diversity assessed through the CAP analysis clearly showed a difference in the bycatch diversity between FAD and the three other fishing modes.

It should be stressed that species composition and size spectrum of tuna captured on FAD and free school sets, as well as the bycatch diversity on these fishing modes has Fonteneau *et al.* 2013 Torres-Irineo *et al.* 2014 Lezama-Ochoa *et al.* 2015). Results presented in this study confirm those of previous works. Setting on FADs mostly results in the successful capture of the tuna school, as it stays aggregated within a few meters under the FAD. The average catch per positive set was however similar or lower (WIO) than on free school sets. In addition, the catch was composed of only adult skipjack 5.2 5.3 5.1 5.2). Positive sets for tuna also mostly captured bycatch, with higher bycatch species richness 5.1). Setting on free schools, on the other hand, presents more risk of the tuna school escaping the net (i.e. diving, swimming away) before its closure. Contrary to FAD sets, the catch is mostly composed of mono-specific schools 5.2 5.3 5.1 5.2). In addition, only a third of the positive sets have bycatch and in these cases two taxa are, on average, incidentally captured per set. The principal goal of this study was however to characterize the species and size composition of targeted tuna species, as well as bycatch diversity captured on whale associated and whale shark associated sets. This will be discussed in the following sections in regards to the findings presented for FAD and free school sets.

5.4.1 Whale associated set

As previously supposed, whale associated sets presented patterns of tuna catch similar to free school sets. However, the main difference was that whale associated sets captured the highest tuna biomass per positive set (29 and 38 t of tuna) of the four fishing modes performed in the EAO and WIO. This fishing mode however also presented high risk of failure (20–31% of the sets) when encircling tuna schools, similar to free school sets. Tunas and baleen whales are usually found in foraging association. Therefore when skippers locate a baleen whale, they may set in its vicinity in order to catch the associated tuna school. The whale mainly escapes by itself by diving or going through the net, sometimes leading the tuna school to follow it. When the tuna school is successfully encircled by purse-seiners, the species and size composition of targeted tunas were the same as on free school sets. The majority of the schools were mono-specific (75%) and most of them consisted of large yellowfin tunas (72%) or large bigeye tunas (4% in the EAO). Baleen whale species that have been recorded to associate with tunas are *Balaenopteridae* (Bryde's whale

Balaenoptera edeni, fin whale *B. physalus*, sei whale *B. borealis*, and humpback whales *Megaptera novaeangliae* Escalle *et al.* 2015). This is the fastest swimming family of baleen Goldbogen *et al.* 2008). This mode of filter feeding is characterized by acceleration toward prey when opening the mouth, as a certain speed (>3 m.s^{-1} Goldbogen *et al.* 2006 2008). Large tuna species would therefore more likely be able to swim along baleen whales (up to 15 m.s^{-1}). For instance, yellowfin tunas may reach speeds up to 22 m.s^{-1} Walters and Fierstine 1964). Smaller sized tunas, such as skipjack, on the other hand routinely swim at speed <1.5 m.s^{-1} Matsumoto *et al.* 2014). While skipjack are also capable reaching speed of 6–10 m.s^{-1} Yuen 1966), the energetic cost associated with it may limit the duration of these high swimming speeds. This may thus explain the fact that less skipjack tunas were found in whale associated sets (17–24% of the mono-specific set). Finally, 25% of all whale associated sets were composed of a mix of medium and large yellowfin (∼50% of the catch), skipjack (∼35%) and bigeye tunas (<15%). This disagrees with a previous study in the WIO, where 78% of the whale associated sets (45 sets studied) were multi-specific, with mostly skipjack Romanov 2002).

Regarding bycatch, half of the positive whale associated sets also contained bycatch. This is higher than on free school sets, but is still less frequent than on FAD sets. As for the tuna catch, the pattern of alpha (rarified number of taxa, abundance, PIE, Simpson's evenness) and beta diversity (CAP analysis) in the bycatch of whale associated sets were 5.1 5.5 5.6). While 2.4 taxa on average per whale associated set were recorded in both oceans, the Simpson's evenness was higher in the WIO (0.9) than in the EAO (0.6). Indeed, one species (*C. falciformis*), although the most abundant in both oceans, was also highly dominant in most whale associated sets of the WIO. In addition, some interesting patterns between oceans and fishing modes may also be identified for this species. In the WIO, *C. falciformis* occurrence is higher on FAD than other fishing modes but the number of individuals per set is similar to megafauna associated sets (∼ 5.1). In the EAO, occurrence is, this time similar, for whale and FAD sets, but the number of individuals per set is higher in whale associated sets (24 ±5.8 against 4.3 ±0.2 for FAD). In addition, the size of the individuals captured was also 5.7). It should be noted that in the WIO while some large individuals were still recorded on free school sets (too low number of megafauna associated sets to observe this), the peak in *C. falciformis* 5.7). This may be an indication of i) a mismatch in the distribution area of juveniles and adults (i.e. outside fishing areas), or ii) a decrease in the *C. falciformis* population. The WIO was found to have the highest

Dagorn *et al.* 2013), as well as high Filmalter *et al.* 2013). Regarding the other bycatch taxa captured, billfishes, chondrichthyans, sunfishes, porcupinefishes and pufferfishes were found among the most abundant taxa. This differed highly from FAD and free school sets, as pelagic bony fishes (i.e. *balistidae*, *carangidae*, *coryphenidae*) found in high number, mostly composed the bycatch on these fishing modes. In free school sets, a sailfish species was nonetheless the 3rd Gaertner *et al.* 2002), which was similar in whale associated sets. Finally, taxa characterizing FAD sets (i.e. *C. maculata*, *C. crysos*, *E. bipinnulata*, *A. stellaris*, *C. hippurus*) were found in less than five sets, and may thus not represent the bycatch community on whale associated sets, but rather might have been Girard *et al.* 2004).

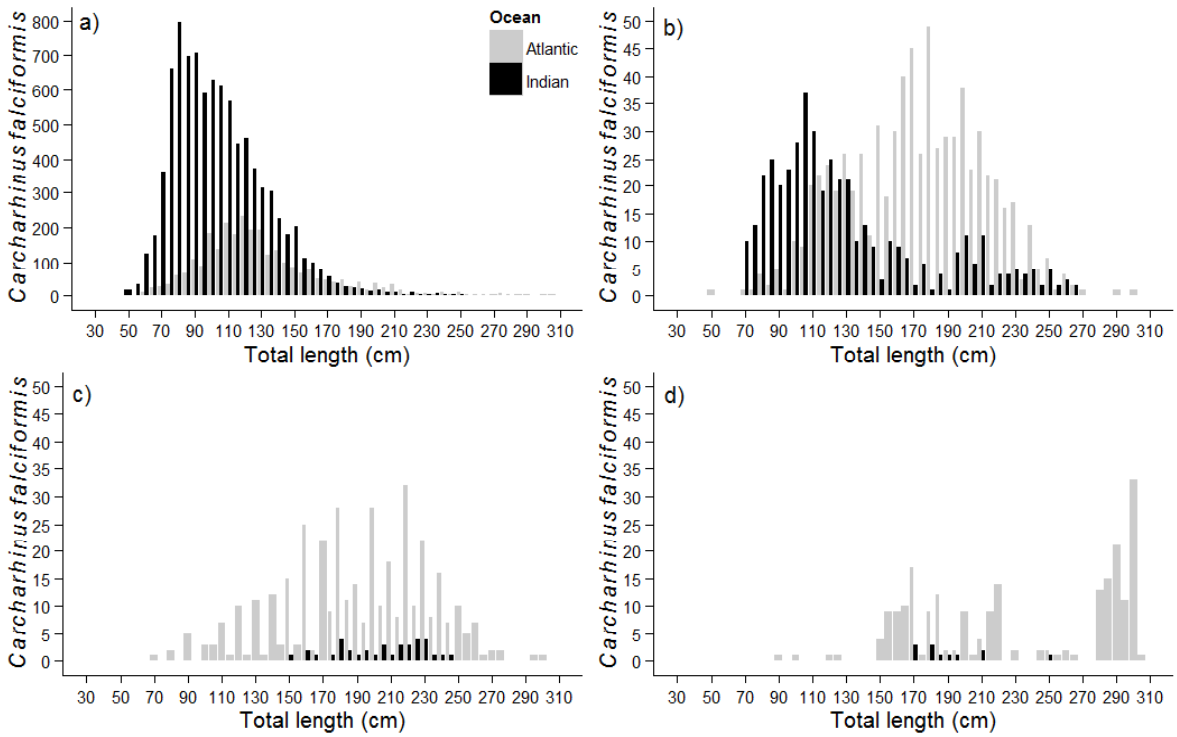


Figure 5.7 Size spectrum of *Carcharhinus falciformis* captured by ocean in the different fishing modes: a) fish aggregating device set, b) free school set, c) whale associated set and d) whale shark associated set.

5.4.2 Whale shark associated set

The catch on whale shark associated sets was more similar to FAD sets, and therefore differed from what was presented for whale associated sets. Setting on whale sharks was more often successful in the EAO than in the WIO. Overall this pattern was observed for all fishing modes, and may be explained by the oceanography and variability of the latter

ocean. Similarly to FAD sets, the percentage of successful sets may indicate that the tuna school, as well as other species, remains aggregated around the whale shark during the setting. Moreover, whale shark associated sets presented the lowest average tuna catch per positive set. As for FAD sets, most whale shark associated sets catch were composed of i) a mix of mostly skipjack (50%), yellowfin (38%) and bigeye (10%) tunas, ii) of only skipjack, or iii) of only yellowfin. It should however be stressed that in general yellowfin tunas were mostly large (> 30kg) and medium (10–30 kg) sized, compared to the majority (∼50%) of 5.1 5.2, Appendix 5.C). This difference with FAD sets might be explained by i) the fact that whale sharks are moving, while they are slower than whales (mean swimming speed < 1 m.s^{-1} and up to 3 m.s^{-1} Rowat and Brooks 2012 Meekan *et al.* 2015) they do not completely act as "living FADs", and ii) whale sharks spend most their time in sub-surface (i.e. 0–10m, ∼50% and in depth of 10–60 m (∼ Gleiss *et al.* 2011 Tyminski *et al.* 2015). Therefore, whale shark associated sets may be somewhat considered intermediate between FAD and free school sets. Moreover, it should be 5.1), was also intermediate between FAD and free school sets, due to the presence of small individuals and the fact that the weight of the whale shark in the net can damage tunas.

Regarding bycatch, the percentage of positive sets with bycatch was, again, the same for whale shark associated and FAD sets (>88%). However, the pattern of alpha and beta diversity in the bycatch of whale shark associated sets, was this time similar to free school and 5.1 5.5 5.6). The rarified number of taxa in the EAO, nonetheless indicated diversity slightly higher for whale shark sets (11.3 ±1.6) than the two other fishing modes (8.5–9.6 ±1.7). Additional whale shark associated sets, as well as whale associated sets, are however still needed to confirm the pattern observed, as the asymptote is far from reached in the taxa accumulation curves. This may thus allow for better estimation of the diversity of bycatch that could be encircled in these fishing modes. As for whale associated sets, the most abundant bycatch taxa on whale shark associated sets was *C. falciformis*. While even on whale associated and free school sets, most *C. falciformis* Bonfil 2008), a peak for large individuals (>270 cm) was found in whale shark associated sets. The reason for the presence of some larger individuals in whale shark associated sets compared to whale and free school sets remains unknown. However, the association between whale sharks and other shark Colman 1997 Rowat and Brooks 2012). The other main species of bycatch were also similar to whale associated sets: chondrichthyans and pufferfishes. However marlins were mostly found instead of sailfishes (as for FAD sets). Finally, pilot fishes, which frequently associate with whale sharks, were, as expected, also

found in these sets. We may therefore conclude that while the tuna catch, as well as number of sets with bycatch, was relatively similar to FAD sets, the diversity and tonnage of bycatch on whale shark associated sets differed from this fishing mode, reinforcing the idea of an intermediate status of whale shark associated sets.

In both megafauna associated sets presented, the most abundant bycatch taxa was the silky shark. We have already mentioned that the occurrence of this species was less frequent in these fishing modes than on FAD sets but when present higher numbers and larger individuals were captured. Other vulnerable or endangered species were however captured, but more rarely, in all fishing modes. This is for instance the case for manta rays, with high differences depending on the ocean and the fishing mode. Indeed in the WIO, their occurrence was higher in free school sets (8.6% of the sets), followed by whale and whale shark associated sets (6.7%) than on FAD (1.8%). In contrast, in the EAO, the occurrence was higher in whale and whale shark associated sets (4.5 and 4.1%) compared to FAD and free school sets (3.0 and 2.9%). As baleen whale and whale shark sets are mostly found in Escalle *et al.* 2016b), their spatial co-occurrence (and possible association) with other filter feeding megafauna species is not surprising. This should however be investigated in more detail, especially the inter-ocean differences regarding free school sets and the generally lower occurrences in the EAO.

This study assessed the catch and bycatch of the European tropical purse-seine fishery in the EAO and WIO, by comparing the four fishing modes as well as the two oceans. A special focus was made on whale and whale shark associated sets, as there were a lack of information on the related catch and bycatch on these fishing modes. Overall, it was found that for all fishing modes, the capture of targeted species as well as the bycatch diversity were higher in the WIO than in the EAO. The number of megafauna associated sets recorded in the observer dataset was however relatively low in the WIO, which may have limited an exhaustive assessment of the bycatch in this area. It would also have been interesting to study the spatial variability of bycatch diversity and tuna catch composition, as well as the potential variation depending on the whale's species, but this was not possible here considering the low number of whale associated sets with the whale species identified. In addition, bycatch diversity (alpha, beta and gamma) was investigated in terms of species richness and evenness, it would have been relevant to also consider functional and taxonomic or phylogenetic diversity. Indeed, species number or evenness are important diversity facets, but do not account for endemic species, functionally or evolutionary close species. This was however not possible with our data due to i) the lack of functional information or biological

data for all species, ii) several taxonomic levels considered (species but also genus), iii) several orders included (chondrichthyan, osteichthyan and reptiles), and iv) the lack of available molecular data for all species.

Whale associated sets were found to be very similar to free school sets. These fishing modes present high risks of failure (tunas escaping), but mainly catch large yellowfin tunas, with bycatch present in half the sets. Main differences between whale and free school sets were found i) in the bycatch taxa captured, ii) whale associated sets capture higher tonnage of tuna per set in both oceans, as well as higher bycatch (tonnage and percentage of the total catch) in the EAO. Whale shark associated sets, on the other hand, were similar to FAD sets in terms of tuna captured, but differed in terms of bycatch. These two fishing modes present less risks of failure but catch lower tonnage of tuna per set and almost systematically present bycatch. Whale shark associated sets however catch larger tunas than FAD sets and a lower amount of bycatch. Finally, both megafauna associated sets have higher catch rates of vulnerable species, such as silky sharks or manta rays and few small fish species. They may therefore have higher impact on the pelagic ecosystem than presumably supposed. Hence, despite the fact that megafauna associated fishing sets have great similarities with the two other fishing modes, their association with other pelagic species is relatively different, especially for whale shark sets, than the ones found on free swimming tuna schools or associated with floating objects.

Acknowledgements

The authors are grateful to the skippers and fishing companies and to Terres Australes et Antarctiques Françaises (TAAF) involved in the logbook data collection, which is supported by the French and Spanish National Fisheries Administrations and research institutes (IRD/IEO/AZTI). We should also like to thank the teams of the "Observatoire Thonier" (IRD), the "Centro Costero de Canarias" (IEO) and AZTI for providing logbook and scientific observer data. L. Escalle is funded by a PhD grant from the University of Montpellier.

Appendix 5.A

Species list

Taxonomic groups	Taxa	Abundance	Occurrence	% of set based on estimated Ab.[1]	Distribution	Fishing mode occurrence FAD	FSC	WHA	WHS
Billfishes	*Istiophoridae*[2]	256	187	0	AO & IO	X	X	X	X
	Istiophorus albicans	2108	631	2.2	AO	X	X	X	X
	Istiophorus platypterus	120	79	0	IO	X	X	X	
	Makaira indica	473	311	5.3	AO & IO	X	X	X	X
	Makaira mazara	3	2	0	IO	X			
	Makaira nigricans	1282	922	0.6	AO & IO	X	X	X	X
	Tetrapturus albidus	9	7	0	AO	X	X		
	Tetrapturus angustirostris	15	13	0	AO & IO	X	X		
	Tetrapturus audax	90	60	1.8	IO	X	X	X	
	Tetrapturus pfluegeri	13	9	0	AO	X	X		
	Xiphiidae				AO & IO				
	Xiphias gladius	174	121	0	AO & IO	X	X	X	X
Cephalopods	*Cephalopoda*	2	2	0	AO & IO				
Other fishes	*Balistidae*[2]	106381	506	11.2	AO & IO	X	X	X	X
	Abalistes stellaris	25175	195	26.3	IO	X	X	X	
	Balistes carolinensis	18555	358	11	AO	X	X		
	Balistes punctatus	7885	39	23.7	AO	X			
	Canthidermis maculata	826864	4153	18.3	AO & IO	X	X	X	X
	Belonidae[2]	156	48	0	AO & IO	X	X		
	Ablennes hians	203	60	1.7	AO & IO	X	X		X
	Tylosurus crocodilus	247	40	0	AO & IO	X	X		
	Bramidae[2]	101	9	0	AO & IO	X	X		
	Brama brama	2	1	0	AO & IO	X			
	Carangidae[2]	14669	196	7.1	AO & IO	X	X		
	Carangoides orthogrammus	5	4	0	IO	X			
	Caranx crysos	641574	1914	26.1	AO	X	X	X	
	Caranx sexfasciatus	3852	186	3.4	IO	X	X		
	Decapterus sp.[2]	4	2	0	AO & IO	X			
	Decapterus macarellus	30909	605	6.2	AO & IO	X	X		
	Elagatis bipinnulata	413977	4368	16.9	AO & IO	X	X	X	X
	Naucrates ductor	58	39	0	AO & IO	X	X	X	X
	Seriola rivoliana	31885	773	3.9	AO & IO	X	X		
	Uraspis sp.[2]	1004	88	6.2	AO & IO	X			
	Uraspis helvola	90	16	0	AO & IO	X			
	Uraspis secunda	36497	691	8	AO & IO	X	X		X
	Uraspis uraspis	99	6	0	IO	X			
	Coryphaenidae[2]	1418	190	0	AO & IO	X	X		X
	Coryphaena equiselis	5834	211	11.5	AO & IO	X	X	X	X
	Coryphaena hippurus	91062	4195	8.2	AO & IO	X	X	X	X
	Diodontidae[2]	626	74	0	AO & IO	X	X	X	
	Diodon eydouxii	2	2	0	AO & IO	X			
	Diodon hystrix	487	100	0	AO & IO	X	X	X	X
	Echeneidae[2]	78	40	0	AO & IO	X	X	X	X
	Echeneis naucrates	153	60	0	AO & IO	X	X		X
	Phtheirichthys lineatus	203	4	0	AO & IO	X			X
	Remora remora	177	87	0	AO & IO	X	X	X	X
	Remorina albescens	3	3	0	AO & IO		X	X	
	Ephippidae[2]	35	10	0	IO	X			
	Platax sp.[2]	837	71	1.5	IO	X			
	Platax teira	4170	219	2	IO	X	X		
	Exocoetidae	20	9	0	AO & IO	X	X		
	Gempylidae				AO & IO				
	Gempylus serpens	16	8	0	AO & IO	X	X		
	Ruvettus pretiosus	659	48	0	AO & IO	X	X		
	Kyphosidae				AO & IO				
	Kyphosus sp.[2]	4100	153	10.2	AO & IO	X	X		
	Kyphosus cinerascens	7629	371	5.8	IO	X	X		
	Kyphosus sectatrix	7515	313	12	AO	X	X		
	Kyphosus vaigiensis	7116	261	7.5	IO	X	X		
	Lampridae				AO & IO				
	Lampris guttatus	3	3	0	AO & IO	X			
	Lobotidae				AO & IO				
	Lobotes surinamensis	14941	1923	4.4	AO & IO	X	X	X	X
	Molidae[2]	3	3	0	AO & IO	X			
	Masturus lanceolatus	70	56	1.9	AO & IO	X	X	X	X
	Mola mola	166	132	3.1	AO & IO	X	X	X	X
	Ranzania laevis	565	14	0	AO & IO	X	X		

Taxonomic groups	Taxa	Abundance	Occurrence	% of set based on estimated Ab.[1]	Distribution	Fishing mode occurrence FAD	FSC	WHA	WHS
	Monacanthidae				AO & IO				
	Aluterus monoceros	10921	722	4.2	AO & IO	X	X	X	
	Aluterus scriptus	1616	123	0.8	AO & IO	X	X		
	Scombridae[2]	258	28	0	AO & IO	X	X		
	Acanthocybium solandri	41989	3146	6.5	AO & IO	X	X	X	X
	Sarda sarda	8	2	0	AO	X	X		
	Scomber japonicus	20	1	0	AO & IO	X			
	Scomber scombrus	20	5	0	AO	X	X		
	Serranidae[2]	8	5	0	AO & IO	X			
	Sphyraenidae[2]	229	43	0	AO & IO	X	X		
	Sphyraena barracuda	8943	1190	4.4	AO & IO	X	X	X	
	Tetraodontidae[2]	72	4	0	AO & IO	X	X		X
	Lagocephalus lagocephalus	832	26	8.3	AO & IO	X	X	X	X
Rays	*Unidentified ray*	24	13	0	AO & IO	X	X	X	
	Dasyatidae[2]	45	37	0	AO & IO	X	X	X	
	Pteroplatytrygon violacea	292	229	0.4	AO & IO	X	X	X	X
	Mobulidae[2]	5	2	0	AO & IO	X	X		
	Manta sp.[2]	6	4	0	AO & IO		X		
	Manta alfredi	2	2	0	IO		X		
	Manta birostris	144	105	0	AO & IO	X	X	X	X
	Mobula sp.[2]	175	116	0	AO & IO	X	X	X	X
	Mobula japanica	110	73	0	AO & IO	X	X	X	X
	Mobula mobular	30	22	0	AO	X	X	X	
	Mobula tarapacana	18	12	0	AO & IO	X	X		
	Rhinopteridae	2	2	0	AO & IO	X	X		
Sharks	*Unidentified shark*	770	104	0	AO & IO	X	X	X	
	Carcharhiniformes[2]	135	24	0	AO & IO	X	X		
	Carcharhinidae[2]	1657	273	2.4	AO & IO	X	X	X	X
	Carcharhinus falciformis	21031	3208	3.1	AO & IO	X	X	X	X
	Carcharhinus leucas	43	6	0	AO & IO	X	X		
	Carcharhinus longimanus	310	195	0.5	AO & IO	X	X	X	
	Galeocerdo cuvier	5	5	0	AO & IO	X	X		
	Prionace glauca	160	122	0	AO & IO	X	X	X	X
	Sphyrnidae[2]	47	25	0	AO & IO	X	X	X	
	Sphyrna lewini	711	176	0	AO & IO	X	X	X	
	Sphyrna mokarran	169	32	0	AO & IO	X	X		
	Sphyrna zygaena	311	96	1.3	AO & IO	X	X	X	X
	Lamniformes[2]	2	2	0	AO & IO		X		
	Alopidae[2]	1	1		AO & IO	X			
	Alopias vulpinus	4	3	0	AO & IO	X			
	Lamnidae				AO & IO				
	Carcharodon carcharias	3	3	0	AO & IO	X			
	Isurus sp.[2]	1	1	0	AO & IO		X		
	Isurus oxyrinchus	62	59	0	AO & IO	X	X	X	X
	Lamna nasus	1	1	0	AO & IO	X			
	Megachasmidae				AO & IO				
	Megachasma pelagios	1	1	0	AO & IO		X		
	Squaliformes[2]	1	1	0	AO & IO	X			
	Etmopteridae				AO & IO				
	Etmopterus sp.	1	1	0	AO & IO	X			
Turtles	*Unidentified turtle*	35	31	0	AO & IO	X	X		
	Cheloniidae[2]	8	8	0	AO & IO	X	X		
	Caretta caretta	117	93	0	AO & IO	X	X	X	
	Chelonia mydas	73	68	2.9	AO & IO	X	X	X	X
	Eretmochelys imbricata	34	34	0	AO & IO	X	X	X	
	Lepidochelys kempii	39	27	0	AO	X	X	X	
	Lepidochelys olivacea	313	239	0	AO & IO	X	X	X	X
	Dermochelyidae				AO & IO				
	Dermochelys coriacea	41	40	0	AO & IO	X	X		

[1] Percentage of the sets with the taxa present, where the abundance was calculated based on the weight of the taxa captured. For the rest of the sets, the abundance was directly estimated (or counted when <100 individuls) by the observer.

[2] The abundance recorded for these taxa was redistributed among the lowest taxonomic level present by sub-region and fishing mode.

AO: eastern Atlantic Ocean, IO: western Indian Ocean, FAD: fish aggregating device, FSC: free school set, WHA: whale associated set, and WHS: whale shark associated set.

Appendix 5.B

Canonical Analysis of Principal Coordinates

Table 5.B.1 Results of Canonical Analysis of Principal Coordinates (CAP) examining the effects of the cross modalities of fishing mode and ocean, when taking into account the maturity of the species captured.

Allocation success %								Manova	m	% Var	δ^2	P
FAD EAO	FAD WIO	FSC EAO	FSC WIO	WHA EAO	WHA WIO	WHS EAO	WHS WIO	p-value				
83.8	87.7	55.9	39.7	30.6	0	14.3	0	$< 2.0e^{-16}$	53	98.4	0.69	0.001

Allocation success = percentage of points correctly allocated into each group, %Var = percentage of the total variation explained by the first m principal coordinate axes, δ^2 = squared canonical correlation, and P = associated probability.
EAO: eastern Atlantic Ocean, WIO: western Indian Ocean. FAD: Fish Aggegating Device set, FSC: free school set, WHA: whale associated set, and WHS: whale shark associated set.

Table 5.B.2 Correlation coefficients for individual taxa ($|r| \geq 0.10$) with the canonical axes 1 and 2 of the Canonical Analysis of Principal Coordinates (CAP), when taking into account the maturity of the species captured.

Taxa	Maturity	Axis 1	Taxa	Maturity	Axis 2
Coryphaena hippurus	AD	0.41	*Caranx crysos*	AD	-0.40
Carcharhinus falciformis	JUV	0.33	*Elagatis bipinnulata*	JUV	-0.30
Sphyraena barracuda	JUV	0.31	*Canthidermis maculata*	AD	-0.29
Decapterus macarellus	AD	0.28	*Acanthocybium solandri*	AD	-0.27
Elagatis bipinnulata	AD	0.27	*Istiophorus albicans*	JUV	0.26
Istiophorus albicans	JUV	-0.25	*Istiophorus albicans*	AD	0.22
Istiophorus albicans	AD	-0.22	*Sphyraena barracuda*	AD	-0.21
Aluterus monoceros	JUV	0.21	*Lobotes surinamensis*	JUV	-0.20
Kyphosus cinerascens	JUV	0.19	*Seriola rivoliana*	JUV	-0.16
Uraspis secunda	AD	0.17	*Acanthocybium solandri*	JUV	-0.16
Caranx crysos	AD	-0.16	*Makaira nigricans*	JUV	-0.16
Canthidermis maculata	AD	0.15	*Caranx crysos*	JUV	-0.15
Acanthocybium solandri	JUV	0.15	*Balistes carolinensis*	AD	-0.14
Lobotes surinamensis	AD	0.14	*Lobotes surinamensis*	AD	-0.12
Kyphosus cinerascens	AD	0.14	*Elagatis bipinnulata*	AD	-0.11
Uraspis secunda	JUV	0.14	*Coryphaena hippurus*	JUV	-0.11
Makaira nigricans	JUV	-0.12	*Prionace glauca*	JUV	0.10
Abalistes stellaris	AD	0.12			
Caranx sexfasciatus	JUV	0.12			
Platax teira	JUV	0.12			
Kyphosus vaigiensis	JUV	0.11			

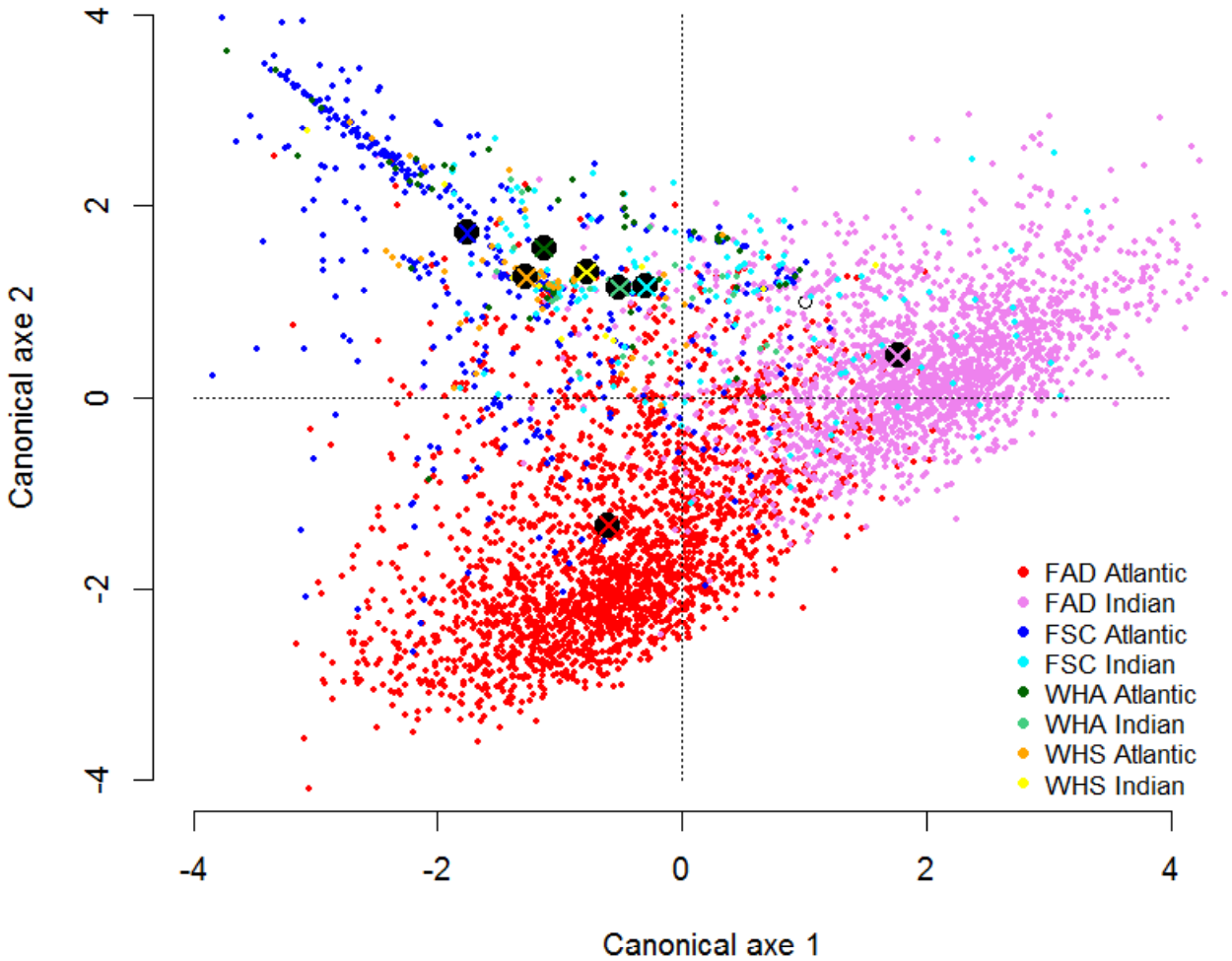
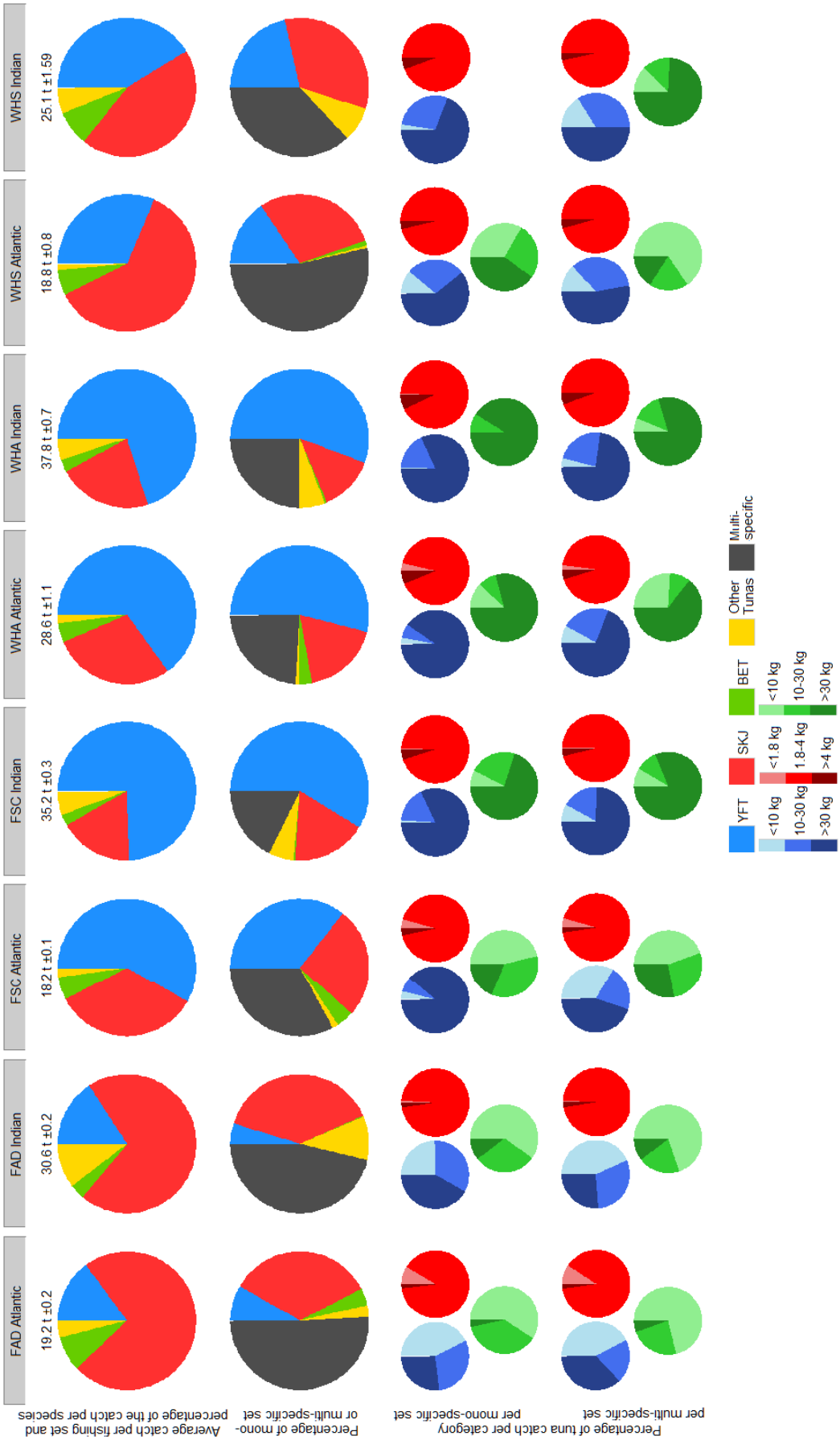


Figure 5.B.1 Two dimensional scatter plot of the axes of the Canonical Analysis of Principal Coordinates (CAP), when taking into account the maturity of the species captured. Crosses represent the barycentres of each modality. FAD: Fish Aggegating Device set, FSC: free school set, WHA: whale associated set, and WHS: whale shark associated set.

Appendix 5.C

Species composition in the tuna catch per mono- or multispecific set, by fishing mode and ocean.



In the last chapter, the targeted and bycatch species captured by the purse-seine fishery in association with whale sharks and baleen whales have been studied. The precise assessment of the main species, size composition and diversity is relevant for management and fishing statistics purposes. In particular, it may be especially important in light of the management measures that have been implemented in both oceans to protect stocks of tropical tunas. These measures were principally oriented toward FAD fishing, but the fishing effort relocation toward other fishing modes (i.e. free school, whale associated and whale shark associated fishing sets) may lead to increasing impacts on encircled megafauna species, but also on associated species. Likewise, conservation measures have been formulated or/and implemented (i.e. in the Indian Ocean) to protect vulnerable and emblematic megafauna species. In the following chapter, the potential side effects and consequences of fishing effort regulation or conservation measures will be investigated. Therefore, it was previously essential to know well the targeted species and size composition, as well as diversity in the bycatch captured in each of the four fishing modes. In addition, findings from other previous chapters of this thesis were also essential as main areas of co-occurrence between the fishery and whale sharks and cetaceans will be used to simulate spatio-temporal conservation measures toward megafauna. The next chapter has also been divided into two different parts. First, the consequences of real (past or current) fishing effort regulation measures (FAD moratoria and no-take zones) on megafauna associated fishing sets will be investigated. Then, consequences of megafauna conservation measures (i.e. spatio-temporal ban of megafauna associated fishing sets) on fishing effort distribution and fleet strategies will be investigated using simulations. Second, larger and longer FAD moratoria will also be simulated to assess potential consequences in term of tuna catch, bycatch, and megafauna associated fishing sets.

Chapter 6

Consequences of conservation or fishing effort regulation measures

Part 1. Consequences of fishing moratoria on catch and bycatch: the case of tropical tuna purse-seiners and whale and whale shark associated sets.

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Published in Biodiversity and Conservation (Article 6)

Escalle, L., Gaertner, D., Chavance, P., Delgado de Molina, A., Ariz, J., Mérigot, B. (2016) Consequences of fishing moratoria on the catch and bycatch: the case of tropical tuna purse-seiners and whale and whale shark associated sets. Biodiversity and Conservation. doi: 10.1007/s10531-016-1146-2

Abstract

Time-area regulations have been introduced to manage stocks of tropical tuna, given the increased use of drifting Fish Aggregating Devices (FADs). However, the consequences in terms of changes in fishing strategies and effort reallocation may not always be as expected. For instance, in the eastern Pacific Ocean, previous studies have highlighted that the increased use of FAD-fishing following the demand for tuna caught without dolphin mortality has raised concerns about the bycatch and the capture of juvenile tuna. In the tropical eastern Atlantic and western Indian Oceans, this study aimed to i) assess, using before-after analysis, the consequences of previous time-area regulations on FAD sets on the fishing effort allocated to megafauna associated sets, and ii) evaluate through Monte Carlo simulations the potential effect of new regulations banning whale or/and whale shark associated sets. Firstly, we showed that previous time-area regulations, which were mainly implemented during seasons with few whale and whale shark associated sets, generally had thus little effect on the number of megafauna associated sets. Secondly, some simulations, particularly when both whale and whale shark associated sets were banned, predicted consequences of changes in fishing strategy. Indeed, these types of ban could lead to an increase in the number of FAD and free school sets but no change in the tuna catch, as well as a slight decrease in bycatch. These results indicate that an ecosystem approach to fisheries, by taking into account megafauna associated sets and bycatch, should thus be adopted when implementing management or conservation measures.

Keywords

Before-after analysis, time-area regulation, Monte Carlo simulation, marine megafauna, purse-seine fishery.

6.1 Introduction

Many marine fish stocks are intensively exploited worldwide, raising concerns about Pauly *et al.* 2002 Branch *et al.* 2011). Various conservation measures and fishing effort restrictions can be introduced to manage the exploited stocks. However, in an EAF, the effect of fishing on non-targeted species FAO 2003). A key issue is the reduction of incidental catches of marine megafauna (e.g. sharks, marine mammals, turtles Lewison *et al.* 2004 2014). The effect of various conservation or management Nowlis 2000 Torres-Irineo *et al.* 2011 Morris and Green 2014 Grantham *et al.* 2008 Werner *et al.* 2015). These include changes in fishing gear and spatial closures. However, it is also essential to assess the potential side effects of these measures on both catch and bycatch species simultaneously.

Tropical purse-seiners detect schools of tuna at the surface of the sea using visual cues, such as flocks of birds, surface water deformation, natural logs or artificial floating objects (i.e. drifting Fish Aggregating Devices FAD) and the presence of megafauna (whale sharks *Rhincodon typus*, baleen whales or pods of dolphins). For data management purposes, the various fishing modes are classified according to the cues for sighting the tuna school. In the eastern Atlantic Ocean (EAO) and the western Indian Ocean (WIO), most fishing sets are made on free-swimming tuna schools ("free school set"), or associated with a floating object ("FAD set"). There are also "whale shark associated sets" (∼1.5% of all fishing sets) and "whale associated sets" (∼ Ariz and Gaertner 1999 Gaertner and Medina-Gaertner 1999 Hallier and Parajua 1999 Capietto *et al.* 2014 Escalle *et al.* 2015). Each fishing mode catches different species and sizes of targeted tuna and bycatch species. In these oceans, free school sets and whale sets mainly catch large yellowfin tuna (*Thunnus albacares* Pallarés and Petit 1998). On the other hand, FAD sets, and to some extent whale shark sets, catch mainly skipjack (*Katsuwonus pelamis*) and juvenile yellowfin and bigeye tuna (*Thunnus obesus*). These fishing modes also incidentally catch a much larger bycatch, including other bony fishes, billfishes, sharks (mainly silky sharks *Carcharhinus falciformis* Amandè *et al.* 2008 2010 Filmalter *et al.* 2013 Bourjea *et al.* 2014).

Various historical regulations to manage the fishing effort have been implemented in the EAO and WIO since the start of tropical tuna purse-seine fishery in the early 1960s and Fonteneau 2009 2010). These included moratoria on FAD sets and the designation of no-take zones to protect juvenile bigeye and yellowfin tuna. In the

western part of the Indian Ocean, increasing piracy has considerably reduced and modified Chassot *et al.* 2010 Kaplan *et al.* 2014) and could also be considered as a time-area closure. Furthermore, the IOTC has banned the intentional setting of purse-seine nets around cetaceans and whale sharks in the WIO (resolution IOTC 13/04 and 13/05). This has been implemented given the ecological importance and vulnerability of these species, as shown by their inclusion in various conservation lists.

Although the direct effects of these fishing effort regulations on tuna catches and Marsac *et al.* 2009 Torres-Irineo *et al.* 2011 Kaplan *et al.* 2014), the side effects of such regulations have not been quantified. For instance, changes in fishing strategies could result in the fishing effort being reallocated to other fishing modes, such as whale or whale shark associated sets, fishing modes that are not currently accounted for by tRMFOs. For example, in the eastern Pacific Ocean, one fishing mode consists in locating, chasing and encircling pods of dolphin in order to catch the associated schools Perrin 1968). High dolphin mortality has led to the "dolphin-safe" label for tuna Hall 1998). The total number of dolphin associated sets decreased and thus considerably reduced dolphin mortality. However an unexpected result was the reallocation of the fishing effort to FAD sets with an increase in the bycatch, discard Edwards and Perkins 1998 Hall 1998).

A global picture of the effects of conventional management and fishing effort regulations is needed at the scale of the fishery and the whole fish assemblage (i.e. catch and bycatch). In such a context, this study set out to i) use before-after analysis to assess the consequences of previous time-area regulations on the fishing effort allocated to whale and whale shark associated sets and ii) use Monte Carlo simulations to evaluate the potential effect of new regulations on whale and whale shark associated sets in terms of the number of sets per fishing mode, the tuna catch per size category and bycatch per taxonomic group. The Monte Carlo approach allows the propagation of the uncertainty in the successive steps of the fishing operations (i.e. fishermen's behavior-at-sea, encounter rate and fishing success for each fishing mode, etc), and consequently produces a range of plausible outputs.

6.2 Materials and methods

6.2.1 Data

Data were obtained from the logbooks of the European tropical tuna purse-seiners (France and Spain), which are the main surface fishing fleets operating in the EAO and WIO, although Ghanaian and Seychelles purse-seiners also operate in these areas. Individual

fishing activities (e.g. setting, moving between fishing areas, etc) have been systematically recorded by skippers since 1990 (90% coverage before this date). These are reported to the IRD for French vessels and the IEO for Spanish vessels. Each fishing set record includes i) the date and geographical location, ii) the cue, i.e. the association between tuna schools and cetaceans, whale sharks, flocks of birds or floating objects (natural log or FADs), and iii) the estimated catch of the set and tuna species composition for each size category (< 10 kg, ≥ 10 kg).

Logbook data are routinely corrected by the IRD and IEO on the basis of samples taken at landing sites. The correction is made to better reflect the species composition per size category over large time and area strata (see below) that are considered homogeneous for the two fishing modes considered. Indeed whale associated sets are combined with free Pallarés and Petit 1998). However, this corrected dataset was not used because i) the data in the logbooks are more representative in terms of size category in the catch for each fishing set, and ii) in the corrected data set the four original fishing modes are reduced to free school sets and FAD sets. As the tuna species may not be correctly identified in the original logbooks, the total tuna catch and the tuna catch per size category were used for the study without detailed consideration of species: tuna < 10kg (a mix of mostly skipjack tuna; juvenile yellowfin and bigeye tuna), and tuna ≥ 10kg (a mix of mostly yellowfin and bigeye tuna).

Data from scientific observers onboard French purse-seiners were also used to assess the composition of the bycatch by large taxonomic groups. These data were collected by the IRD from 2005 to 2014 as part of continuous data collection programs (i.e. the European Union Data Collection Framework; Regulation (EC) No 199/2008). The coverage rate over the period considered was about 23% of all fishing sets in the EAO and 12% in the WIO. For each fishing set, the composition of the bycatch (including discards of the targeted species), was recorded by species when possible, or else by taxonomic group. The composition of the bycatch for each fishing set was then assessed per taxonomic species group as follows: i) other bony fishes (all bony fishes except the targeted tunas species and billfishes), ii) billfishes, iii) chondrichthyans (sharks and rays) and iv) marine turtles. Observer data was only used for bycatch, because i) the 100% logbook coverage rate allows for more representative data for each fishing mode, season and sub-region (see below), ii) the tuna catch registered by scientific observers is the captain's estimation, iii) the rate of whale and whale-shark Capietto *et al.* 2014 Escalle *et al.* 2015).

6.2.2 Sub-regions and periods

The main fishing grounds of the European purse-seiners were divided into 6 sub- 6.1), following the stratification used by Pallarés and Petit (1998) for spatial sampling.

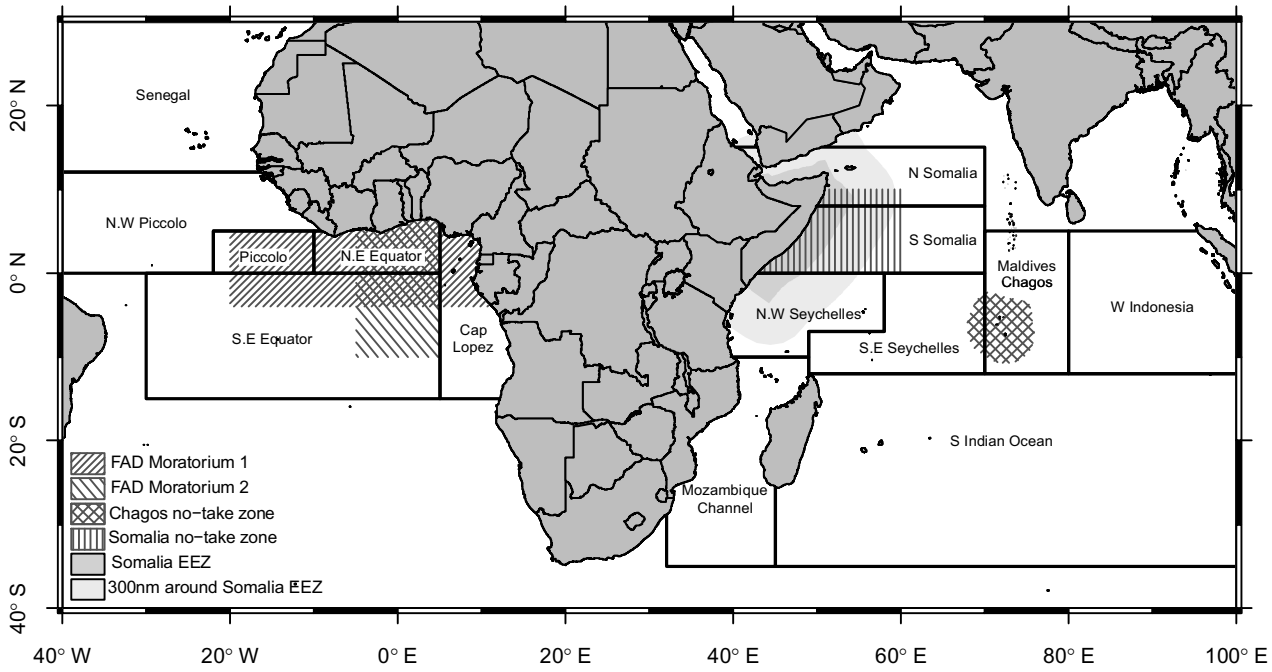

Figure 6.1 Sub-regions used by the European Union research institutes (IRD and IEO) for spatial sampling and regions where time-area regulations on the fishing effort have been introduced by tuna Regional Fisheries Management Organizations (ICCAT and IOTC).

The study also considered regions where fishing effort regulations were introduced 6.1 6.1). Firstly, in the EAO, the increasing number of FAD sets induced large catches of bigeye tuna and juveniles of various tuna Ariz and Gaertner 1999). This led to a voluntary ban on FAD sets taken by the French and Spanish purse-seine fishing companies in 1997, and covering a large area of the tropical EAO (4°S–5°N and 20°W–African coast) from November to January each year. It was then endorsed by the ICCAT in 1999 (ICCAT Rec [98-01] and [99-01]) to protect juvenile bigeye and yellowfin tuna and remained in force until 2005. A second moratorium was then introduced in the EAO in 2012. This is currently still in force but applies to a different area (0–5°N and 20–10°W) and period (January and February) (ICCAT [11-01] and [14-01]). In the WIO, fishing effort regulations have been applied more recently. In addition to declaring Koldewey *et al.* 2010), the IOTC declared a no-take zone (in November) east of Somalia (0–10°N and 40–60°E) to protect yellowfin and bigeye stocks (IOTC resolution 12/13). Both no-take zones are still in

force. Finally, no fishing effort was recorded in the Somalia EEZ between 2005 and 2006, due to the lack of fishing license. This was followed by a reduced fishing effort due to piracy, in a 300 nautical mile buffer around this zone between 2007 and 2009. Therefore, these may be considered to be similar to the effects of introducing fishing effort regulations.

Table 6.1 Consequences of fishing effort regulations introduced in the eastern Atlantic (EAO) and western Indian (WIO) Oceans assessed by a before-after analysis.

Ocean	Regulation	Area	Before	After	Period	**INSIDE** Significant indices	**OUTSIDE** Significant indices
EAO	Moratorium on FAD	4°S–5°N 20°W–African Coast	1992–1996	1997–2005	November to January	↓ FD; ↓ FS; ↓ C^+; ↓ FAD; ↓ $_{FAD}C^+$; ↑ $_{FrSc}C^+$	↑ FD; ↑ FS, ↓ FAD; ↑ FrSc; ↑ $_{FrSc}C^+$
EAO	Moratorium on FAD	10°S–African Coast 5°W–5°E	2009–2011	2012–2014	January to February	↓$_{FAD}C^+$	
WIO	No-take zone	Chagos EEZ	2005–2009	2010–2014	Year-round	↓FD; ↓ FS; ↓ C^+;↓ FAD; ↓ $_{FAD}C^+$; ↓ FrSc; ↓ $_{FrSc}C^+$	↑FAD; ↑ $_{FAD}C^+$; ↓ FrSc; ↓ WHA; ↓ WHS;↓ $_{WHS}C^+$
WIO	No-take zone	0–10°N 40E–60°E	2009–2010	2011–2014	November		
WIO	Piracy (1)	Somalia EEZ	2002–2004	2005–2006	Year-round	↓FD	↑FD;↑ FS
	Piracy (2)	300 n.m. Somalia EEZ	2005–2006	2007–2009	Year-round	↓FS; ↓ C^+; ↓ FrSc;↓$_{FrSc}C^+$; ↓ WHS; ↓ $_{WHS}C^+$	↑FD;↑ FAD

Arrows indicate an increase or decrease in the value of the fishery indices.
FD = number of Fishing days; FS = number of Fishing sets; C^+ = total tuna catch; FAD = number of FAD sets; $_{FAD}C^+$ = FAD set catch; FrSc = number of free school sets; $_{FrSc}C^+$ = free school set catch; WHA = number of whale associated sets; $_{WHA}C^+$ = associated set catch; WHS = number of whale shark associated sets; $_{WHS}C^+$ = whale shark associated set catch

Given the difference in environment in the two oceans, the EAO was stratified into four quarters, starting from January and labeled 1 to 4. Because the WIO is strongly affected by seasonal monsoons, it was stratified into two main monsoon periods [north-east (NE) from December to March (Season 1) and south-west (SW) from June to September (3)], and two inter-monsoon periods [south-west (ISW) in April–May (2) and north-east (INE) in Capietto *et al.* 2014 Escalle *et al.* 2015).

6.2.3 Before-after analysis

For impact assessment studies, a before-after (BA) design is the simplest approach for determining whether a stressor has changed the environment, what components are Smith 2002). This consists of comparing data recorded prior to a natural or anthropogenic change to data recorded after the change. Any statistical difference between the two periods is assumed to indicate the effect Wiens and Parker 1995 Smith 2002). However, changes in the environment Smith 2002). Consequently, to improve the estimate of the change in a given area, a control area

Stewart-Oaten *et al.* 1986). This approach is a before-after-control-impact (BACI) design.

This study assessed the consequences of time-area regulations on the fishing effort, with each of the areas defined being considered as the area affected by the change. However, the implementation of fishing effort regulation may have an effect within and outside the area to which they apply (e.g. changes in fishing strategy or reallocation of fishing effort as a result of the regulations). In this case, it was not possible to define a control zone. Thus, a BA design was used to study the effect of fishing effort regulations on the area to which they Torres-Irineo *et al.* 2011). For each regulation, the data were classified into inside and outside groups. Then it was split into before and after groups (before and during (i.e. "after") the period with the regulation in place). Data from before and after the change were considered as independent samples Smith 2002).

A number of fishery indices were analyzed to determine whether there was any change in the activity or fishing strategy of the purse-seiners: the number of fishing days (FD), the total number of fishing sets (FS), the total tuna catch in tons (C^+), the number of FAD sets (FAD), the FAD tuna catch in tons (${}_{FAD}C^+$), the number of free school sets (FrSc), the free school tuna catch in tons (${}_{FrSc}C^+$), the number of whale associated sets (WHA), the whale associated tuna catch in tons (${}_{WHA}C^+$), the number of whale shark associated sets (WHS) and the whale shark associated tuna catch in tons (${}_{WHS}C^+$). For each type of regulation, these fishery indices were calculated for the four areas / period combinations (inside/before, inside/after, outside/before, outside/after), on a monthly basis. Then they were normalized by the number of vessels operating in a given month.

Wilcoxon tests were used to detect differences in the period before and after the implementation of a regulation i) inside the area where it applied and ii) outside this area. French and Spanish logbooks were analyzed together, as a preliminary analysis of the logbooks for each country gave similar results.

6.2.4 Monte Carlo simulation

6.2.4.1. General principle

The strengths and weaknesses of a regulation, such as a time-area closure or a moratorium on a fishing practice, can be evaluated by simulating the behavior-at-sea of the tuna purse-seiners. The model must include all the steps from selecting a fishing ground to the realization of the set in a decision process. However, the various fishing choices or

risks (e.g. the success of a set for a specific fishing mode) describing purse-seiner fishing operations are difficult to quantify exactly, and thus to predict the effect of a given regulation. In such context, Monte Carlo simulation can be used to propagate uncertainties in model inputs into uncertainties in model outputs. The uncertainties used as inputs are described using probability distributions, which define the range of values a variable may take, and the probability of these values occurring.

Basically, Monte Carlo simulation, consists of drawing a large number of pseudo-random uniform variables (e.g. 1000) from the interval [0,1]. Then it assigns values less than or equal to the observed probability of an event (e.g. setting on a specific fishing mode, having a positive set (i.e. tuna caught), etc). For each simulation, all of the uncertain parameters were sampled. The process was then simulated over time to calculate the outputs of the process, after changing certain probabilities as a result of a regulation. This gave a large number of separate and independent outputs. Each represents one possible path that the process might follow over time. The outputs (e.g. total tuna catch per size category, total bycatch per taxonomic group, number of sets on a protected megafauna species, etc) were assembled into probability distributions of possible outcomes. As a result, the outputs of the model are not single values but probability distributions. These latter can be used to calculate average values and corresponding confidence intervals. Monte Carlo methods Gaertner *et al.* 1996 Vaca-Rodríguez and Dreyfus-León 2000). They also allowed to estimate the amount of Gaertner *et al.* 2002).

6.2.4.2. Conditional Probabilities

Monte Carlo simulations were used in this study to simulate the potential effect of a ban on a specific fishing mode (e.g. whale shark associated set or whale associated set). This was simulated for one fishing season for one vessel from a designated fleet (French or Spanish). French purse-seiners and Spanish purse-seiners have different fishing strategies in terms of fishing modes and spatio-temporal effort distribution. French purse-seiners mainly target free swimming schools but also FAD sets (average of 53% and 44% of all sets, respectively, for the 2005–2014 period). Spanish purse-seiners mainly set on FAD (59%) and to a lesser extent on free schools (41%). However both fleets experience high seasonal, annual and spatial variability in the tuna captured. A diagram of the simulated process is 6.2 6.2. The paths taken through the process depended on the conditional probabilities of the successive

decisions or events that occurred for the vessel during each day: i) presence in the area 6.2), ii) the number of fishing sets completed (2 and 6.2 6.2), iv) the 6.2 6.2 6.2). These were based on probabilities that were calculated using commercial fisheries data from European tuna purse-seiners (logbook and/or scientific observer data depending on the type of probability). To give an up-to-date picture of the situation and strategies of European purse-seiners, the probabilities were calculated for the last ten years. The 2005–2014 period was used for the EAO. For the WIO, as intentional cetacean and whale shark sets have been banned by the IOTC since September 2013 (resolution IOTC 13/04 and 13/05), the period considered was from 2005 to August 2013. During the 2005–2014 period in both oceans, there was high annual variability in the fishing effort and fishing strategy. For instance, the rates of whale and whale shark associated sets were sometimes higher in the past than at present (but occurring during specific season, see 6.3). These simulations were intended to gauge the effect of the implementation of the ban on the recent pattern of fishing activities of European purse-seiners. Therefore the annual variability was not implemented in the simulation but an average of each fishing indices over the 10 year period was used. Conditional probabilities were calculated for each 6.1), season (quarters in the EAO and monsoon or inter-monsoon periods in the WIO), fleet (French or Spanish), and derived from cumulative 6.2 for examples of histograms).

6.2.4.3. Areas and period considered

Various scenarios based on real data from the tuna purse-seine fisheries were designed to simulate the potential effect of fishing bans. Areas and periods chosen to simulate the implementation of a ban on whale or/and whale shark associated sets had already been identified as having a high co-occurrence between megafauna species and the purse-seine fisheries: i) the Cap Lopez sub-region during season 2 and 3 (whale or/and whale shark), ii) the Mozambique Channel sub-region during ISW monsoon period (whale or/and whale shark) and iii) the SE Seychelles sub-region during NE and ISW monsoon period (whale) Capietto *et al.* 2014 Escalle *et al.* 2015 for further information). In addition, whale shark and whale associated sets for the Spanish purse-seiners were found to be spread throughout all sub-regions of the EAO during season 3. Therefore a ban on whale or/and whale shark associated sets covering the whole of the EAO during season 3 was also simulated (based on conditional probabilities obtained from Spanish purse-seiners). Similarly, whale and whale shark associated sets have been recorded in two sub-regions of the western WIO during ISW

monsoon period. Thus a ban on whale or/and whale shark associated sets covering the whole WIO was simulated during ISW monsoon period for both fleets.

Table 6.2 Conditional probabilities and parameters used in the Monte Carlo simulations of bans on whale and/or whale shark associated sets, derived from European purse-seine fishery data.

Symbol	Description
i	Index of day in a regulated fishing season.
I	Total number of days in a regulated fishing season: 90 days in the Atlantic Ocean, 60 or 120 in the Indian Ocean.
j	Index of fishing set completed in day i.
J	Total number of sets j during day i (depends on *Pb*).
C	Tuna catch (t) in size category c ($\leq$10 kg; >10 kg).
B	Bycatch (t) per taxonomic group. Note that a null set (less than 1 t of tuna catch) may have a bycatch.
Pa_{reg}	Probability of fishing activity on day i in the sub-region with regulations[a].
Pa_{L}	Probability of fishing activity on day i in one of the free access sub-regions L[a].
Pb	Probability of completing a given number of fishing sets (J) during day i, per sub-regiona. Pb_0 represents the probability of 0 fishing sets.
Pc	Probability of each fishing mode (FM): FAD, free school, whale associated, or whale shark associated set, per sub-region[a].
Pc'	Adjusted probability of each fishing mode (FM). When one type of fishing mode is banned, the probability of the occurrence of this type of fishing mode is redistributed among the remaining fishing modes according to their probabilities.
Pd	Probability of successful fishing set, for each fishing mode and sub-regiona. The set is either positive (tuna catch) or null (less than 1 t of tuna catch).
Pe	Probability of catching C tons of tuna in the set for each fishing mode and sub-region. Two probabilities Pe_{C1} and Pe_{C2} are used for the two size categories: C1 tuna $\leq$ 10kg and C2 tuna >10kga.
Pf	Probability of catching Bycatch-group B (B1 other fishes (t), B2 billfishes (t), B3 chondrichthyans (t), and B4 turtles (kg)), per fishing mode and sub-region[b]. To account for the presence of bycatch in unsuccessful tuna sets (< 1 t tuna catch), different probabilities were used for successful and unsuccessful sets (Pf_{pB1}, Pf_{pB2}, Pf_{pB3}, Pf_{pB4} and Pf_{nB1}, Pf_{nB2}, Pf_{nB3}, and Pf_{nB4}, respectively).

[a] Because the distribution of fishing effort between regions and fishing modes may differ between French and Spanish vessels, these probabilities were calculated separately from French and Spanish logbooks.
[b] The bycatch for each group, fishing mode and region was assumed to be independent of the fishing fleet. The probabilities were calculated from the French observer data.

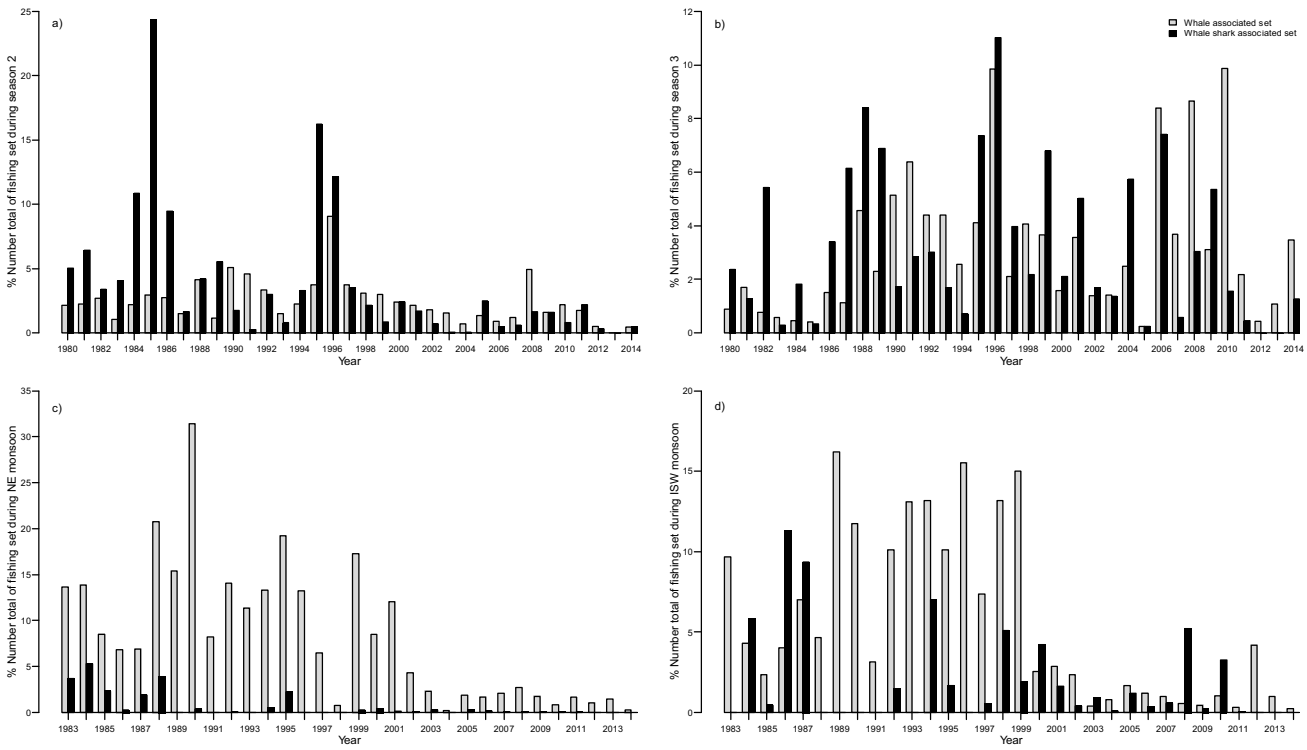

Figure 6.3 Trends of the percentage of whale and whale shark associated sets by the total number of sets per season from 1980 to 2014, during a) season 2 and b) season 3 in the Atlantic Ocean, c) NE monsoon periods and d) ISW inter-monsoon periods in the Indian Ocean.

6.2.4.4. Simulating potential fishing bans on megafauna associated sets

As the aim of this study was to detect the effect of a potential ban on whale or/and whale shark associated sets, a scenario without any ban was tested to reflect the current 6.3) for a particular season and for each sub-region identified. For simulations with a ban on one type of set, the probability of the occurrence of this set was redistributed among the remaining fishing modes proportionate to their respective probabilities (the probability *Pc* of setting on a fishing mode 6.2). Because the fishing strategies and fishing grounds of the French and Spanish purse-seiners might vary throughout the year, each simulation was applied separately for each fleet.

Then, for each scenario, Monte Carlo simulations were carried out 1000 times for the fishing season of one vessel from a designated fleet. Each day i of the fishing season (i = 1 to 90 days in the EAO, or 1 to 60 or 120 days in the WIO, depending on the number of days in the season considered), the vessel may fish in any of the sub-regions. For each day i, a 6.2). The vessel was assumed to spend the day in the area where the virtual ban was implemented (left section in

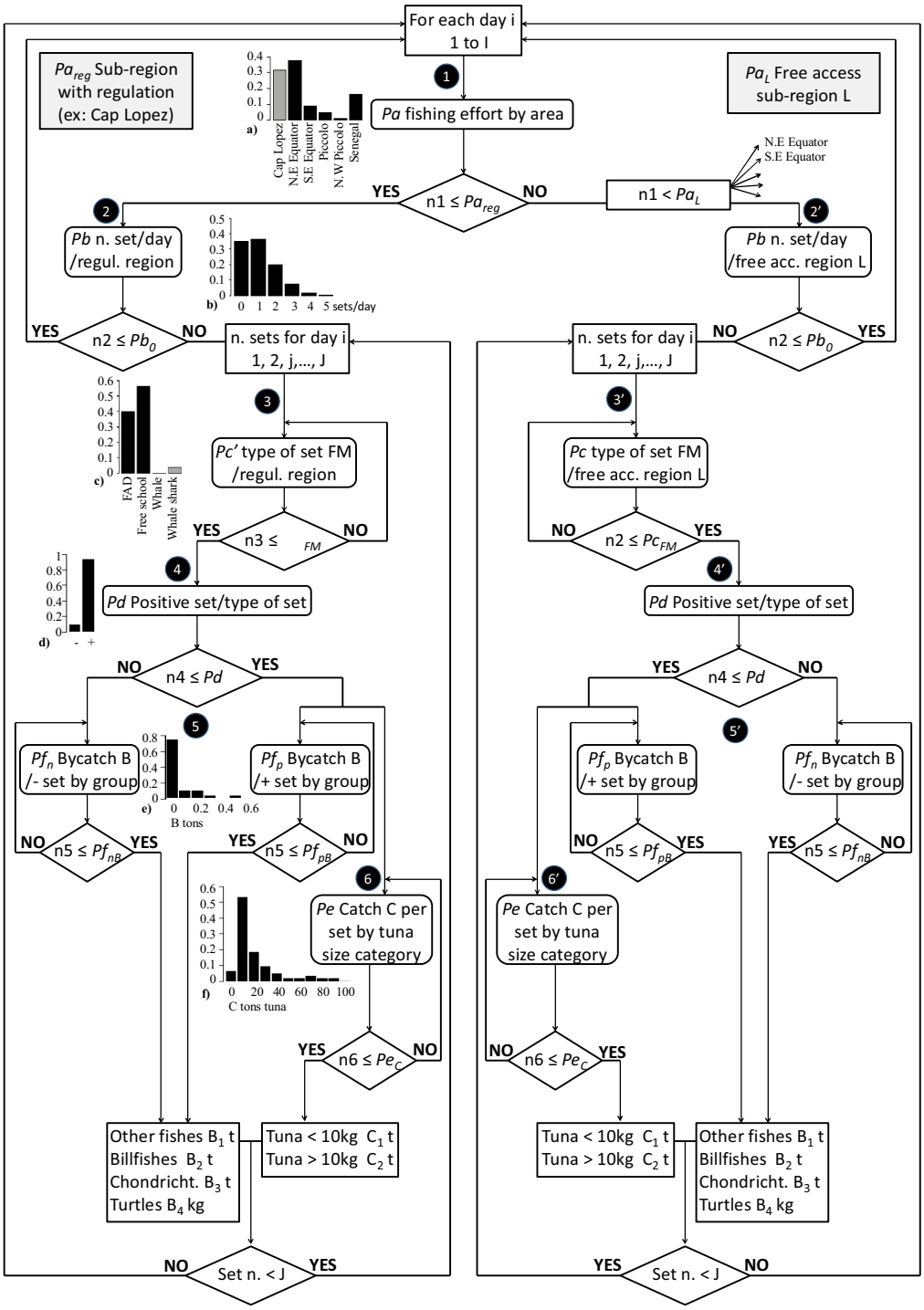

Figure 6.2 Representation of the decision process used for the Monte Carlo simulation. Histograms (illustrative only: for the simulation cumulative histograms are used), given as examples, are probabilities of a) fishing in each sub-region during season 3 in the Atlantic Ocean (*Pa*), b) number of fishing sets per day in Cap Lopez (*Pb* Cap Lopez), c) fishing mode, with a ban on whale associated sets; *Pc*), d) whale shark associated set positive or null (*Pd* /whale shark set), e) bycatch of chondrichthyans in a whale shark associated set (*Pf* chondrichthyans/whale shark set), f) catch of tuna <10kg in a whale shark associated set (*Pe* <10kg/whale shark set). n (n1, n2 ...) are the random numbers drawn and compared to each probability.

6.2 6.2). For computational reasons, the probabilities of binary, categorical or semi-quantitative inputs were previously transformed into cumulative probabilities before drawing the random number. A second number n2 was then generated at random and compared to the probability *Pb* of having j 6.2). If 0 fishing sets was drawn, then the simulation continued directly to the following day (i+1; 6.2). Otherwise j fishing sets were simulated successively. The same process was repeated to determine the fishing mode associated with each set j (n3 vs *Pc*; see 6.2), and whether the set for this fishing mode was successful or not (n4 vs *Pd* 6.2). To characterize the uncertainty in the catch of tuna, as well as in the bycatch, 4 random numbers n5 were generated for all cases (fishing set positive or null, as it was assumed that an unsuccessful set for tuna may have a bycatch, see 5 or 5′ in 6.2). They were then compared to the probabilities Pf_n or Pf_p of having B t of bycatch per species group. If the set was positive, 2 random numbers were generated and compared to the probabilities *Pe* 6.2).

In order to facilitate the comparison between oceans and between fleets, the results in terms of i) the numbers of each fishing mode, ii) the tuna catch for each size category and iii) bycatch per species group were calculated on a vessel basis and by fishing season for all sub-regions taken together. These results were then presented using histograms, comparing the baseline simulation (i.e. in the absence of regulation), and the simulation with one type of set banned. The statistical difference between the two simulated Monte Carlo distributions was then tested using a Kolmogorov-Smirnov test. All the analyses were conducted using R software v.3.0.2 (R Development Core Team 2014).

6.3 Results

6.3.1 Before-after analysis

Overall, the results show that time-area regulations i) affected the number of sets for each fishing mode and the tuna catch of European purse-seine fleet in both the EAO and WIO, and ii) had contrasted effects on the number of whale and whale shark associated sets in each ocean.

Firstly, each of the time-area regulations implemented in the EAO and WIO, as well as piracy, had an effect on the number of sets by fishing mode (FADs, FrSc, WHA and WHS), and the tuna catch (C^+ 6.1). The exceptions were the two most recent regulations (the Somalian no-take zone in the WIO and the second moratorium

6.1).

Secondly, for each of the regulations applying to the EAO, there was no significant effect on 6.1). In the WIO, however, there was some effect outside the area to which the restrictions applied during the period 2010–2014. A decrease was observed in the number of whale and whale shark associated sets (WHA, WHS), and in the whale shark associated set catch ($_{WHS}C^{+}$) when the 6.1). There was also an increase in the number of whale shark associated sets (WHS) and the catch ($_{WHS}C^{+}$) during the period of increasing piracy activity.

Table 6.3 Results of Monte Carlo simulation of bans on whale or/and whale shark associated sets in specific areas and periods of the eastern Atlantic (EAO) and western Indian (WIO) Oceans. Column 6 indicates differences between the simulation of ban on a fishing mode and the baseline simulation).

Ocean	Area covered by regulation	Season	Fleet	Type of set banned	Bans different from baseline	Significant index(K.S. test p-value)
EAO	Cap Lopez	2 (90 days)	French	WHA/ WHS/ both	None	
			Spanish	WHA/ WHS/ both	None	
		3 (90 days)	French	WHA/ WHS/ both	WHA & WHS	↑ FAD ($3.61e^{-06}$)↑ FrSc ($1.53e^{-07}$)↓ chondrichth. ($3.61e^{-06}$)
			Spanish	WHA/ WHS/ both	None	
	Atlantic Ocean	3 (90 days)	Spanish	WHA/ WHS/ both	WHS	↑ FAD ($3.90e^{-03}$)↑ FrSc (0.03) ↑Tuna <10kg ($8.37e^{-03}$)
					WHA & WHS	↑ FAD ($3.26e^{-05}$)↑ FrSc ($1.11e^{-04}$)↑Tuna <10kg ($8.37e^{-03}$)
WIO	Mozambique Channel	ISW (60 days)	French	WHA/ WHS/ both	None	
			Spanish	WHA/ WHS/ both	None	
WIO	SE Seychelles	NE (120 days)	French	WHA	WHA	↑ FrSc ($1.12e^{-06}$)↓ Billfishes ($2.04e^{-03}$)
			Spanish	WHA	None	
	SE Seychelles	ISW (60 days)	French	WHA	WHA	↑ FrSc ($3.90e^{-03}$)
			Spanish	WHA	None	
	Indian Ocean	ISW (60 days)	French	WHA/ WHS/ both	WHA	↑ FrSc ($7.26e^{-04}$)
					WHA & WHS	↑ FrSc ($1.99e^{-04}$)↑ FAD ($8.67e^{-04}$)↓ Billfishes (0.01)
			Spanish	WHA/ WHS/ both	WHS	↑ FrSc ($4.34e^{-05}$)
					WHA & WHS	↑ FrSc (0.02)

Arrows indicate an increase or decrease in the fishery index considered. ISW=south-west inter-monsoon, NE= north-east monsoon, WHA= Whale associated set, WHS= whale shark associated set, FAD= Fish Aggregating Device set, FrSc= Free school set, K.S. test = Kolmogorov-Smirnov test.

Taking each regulation individually, firstly, in the EAO, the first moratorium on FADs led to a decrease in the number of FAD sets inside the moratorium area (from 6.8 sets per 6.1 6.4). The tuna catch on FAD sets also decreased (from 215.5 t per vessel to 60.3 t catch in FAD decreased). However, outside the moratorium area there was also a decrease in the number of FAD sets (during the 3 months of the moratorium

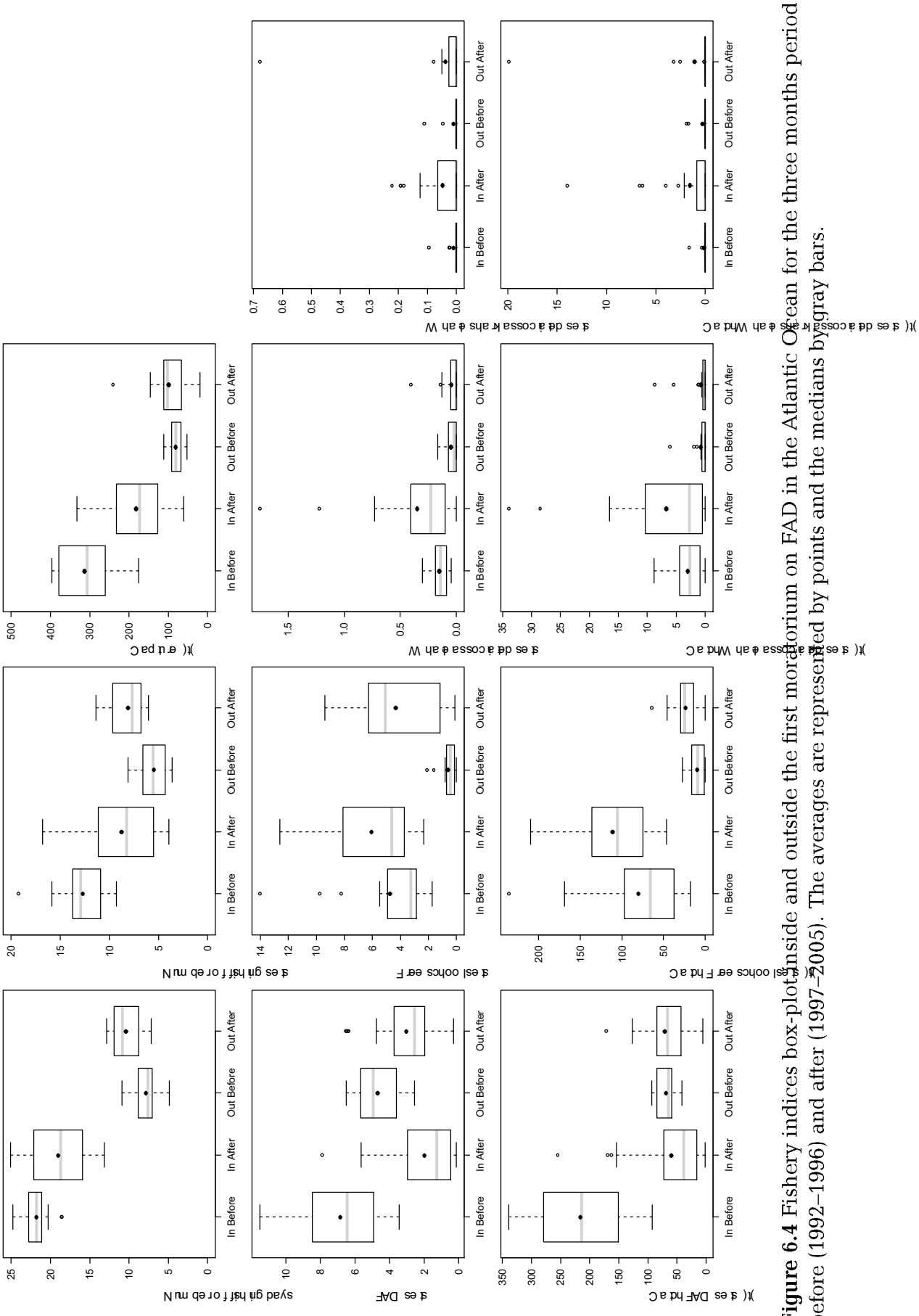

Figure 6.4 Fishery indices box-plots inside and outside the first moratorium on FAD in the Atlantic Ocean for the three months period before (1992–1996) and after (1997–2005). The averages are represented by points and the medians by gray bars.

the average number of FAD sets per vessel decreased from 4.7 to 3.0). In addition, an increase in free school sets (average number of sets increased from 0.6 to 4.3) and catch (average 6.1 6.4) was obtained. For the second FAD moratorium, statistical tests showed no significant differences for any of the fishery indices. An exception was for the FAD tuna catch inside the area, there was an insignificant decrease in the number of FAD sets (2.9 to 0.9), and free school sets (7.1 to 4.9).

Secondly, in the WIO, the introduction of the Chagos no-take zone reduced the

6.1). Likewise the tuna catch was reduced (from 32.6 t to 10.3 t for FAD sets, and from 67.1 t to 1.3 t per year and vessel for free school sets). In the free access areas of the WIO, there was an increase in FAD sets (11.7 to 15.5) and catch (363.0 t to 447.4 t). A moderate decrease in other sets was also observed: free school sets (8.7 to 5.9), whale associated sets (0.3 to 0.2 sets) and whale shark associated sets (0.1 to 0.0). For the Somalia no-take zone, the statistical tests showed no significant differences. However, the boxplots suggested that the decrease in FAD sets inside the no-take zone (from 8.2 to 0 sets) led to an increase outside the area (6.8 to 16.6). During the first period of piracy, when no licenses had been granted for fishing in the Somalia EEZ, there was a decrease in the number of days spent inside the 6.1). In addition an increase in the number of days spent outside the EEZ occurred (20.9 days to 23.8). During the second period of piracy (piracy activity up to 300 nautical miles off the Somalia EEZ), the effect was more marked with a general decrease in the various fishery indices inside the area where there was a risk of piracy. Indeed there was a reduction in free school sets (4.3 down to 1.7) and catch (103.1 t down to 34.1 t). Likewise, whale shark associated sets (0.1 down to 0.0) and catch (2.2 t down to 0.0) decreased. However, similarly to the first piracy period, the number of FAD sets increased significantly in the free access areas (from 4.5 to 6.7 sets).

6.3.2 Monte Carlo simulation

Simulating the introduction of a ban on setting on one type of megafauna gave 6.3). Some Monte Carlo simulations did not differ from the baseline. For instance, in the EAO, it was the case for Cap Lopez season 2 for both fleets, season 3 for Spanish fleet. Likewise in the WIO, it occurs for Mozambique Channel (both fleet) and SE Seychelles (Spanish fleet) during the ISW monsoon period, and SE Seychelles (Spanish fleet) during the NE monsoon period. However, other simulations gave predictions that differed slightly from the baseline (see 6.5 6.6 6.7 as examples). Indeed, an increase in the number of FAD and/or free

school sets occurred. In addition, the amount of bycatch of some groups (chondrichthyans or billfishes) decreased. Likewise, the tuna catch sometimes differed from the baseline.

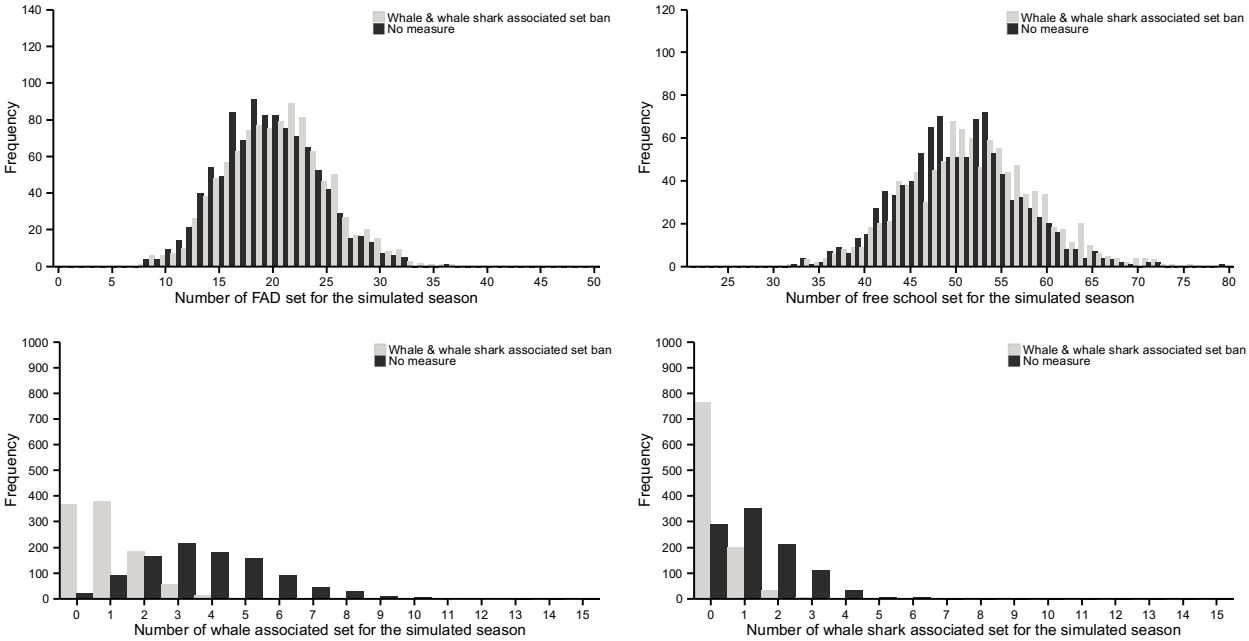

Figure 6.5 Simulated number of fishing sets by one French purse-seiner during season 3, for a moratorium on whale and whale shark associated sets in Cap Lopez, compared to the baseline.

For example, in the EAO in the Cap Lopez sub-region during season 3 for the French purse-seiners, modeling predicted that a ban on whale and whale shark associated sets would lead to a slight increase in FAD and free school sets, and a small decrease in chondrichthyan 6.5 6.6 6.7). For the Spanish purse-seiners during the same season 3, a ban on either whale shark or whale and whale shark associated sets in the whole EAO would result in a change in fishing strategy. A small increase in the number of FAD sets and free school sets (from an average of 32.7 and 24.6 sets per season, respectively, to 33.4–33.9 6.3), as well as in the amount of tuna < 10 kg caught (from 1244 t to 1274 or 1267 t) was detected.

In the WIO during the NE or ISW monsoon periods for the French purse-seiners, introducing a moratorium on whale associated sets in the SE Seychelles sub-region would lead to a slight increase in the number of free school sets. Indeed a change from an average of 66.4 sets per vessel and season to 68.9 during the NE monsoon period was obtained, and from 26.7 sets to 27.5 during the ISW monsoon period. In addition, a slight decrease in the amount of billfishes caught occurred (from an average of 2.1 t captured per vessel and season to 1.9 t during the NE monsoon period). For the Spanish purse-seiners, only a regulation that applied to the whole WIO during the ISW monsoon period was significantly different

from the baseline. A separate ban on whale shark associated sets, as well as on whale and whale shark sets, slightly increased the number of Spanish free school sets. Indeed, a change from an average of 24.8 free school sets in the absence of regulations to 25.8 was obtained. Likewise, it reached 25.5 sets when whale shark and both whale and whale sharks associated sets were banned, respectively. For the French purse-seiners, the effects of introducing the same regulation (i.e. whole WIO during the ISW monsoon period) were significant when whale sets or both whale and whale shark sets were banned. In both cases, the number of free school sets increased (from an average of 26.9 sets per vessel to 28.1). In addition, when both sets were banned, the number of FAD sets also increased (from an average of 27.3 sets per vessel to 28.3). The bycatch of billfishes decreased slightly (from 0.9 t to 0.8 t per vessel 6.3).

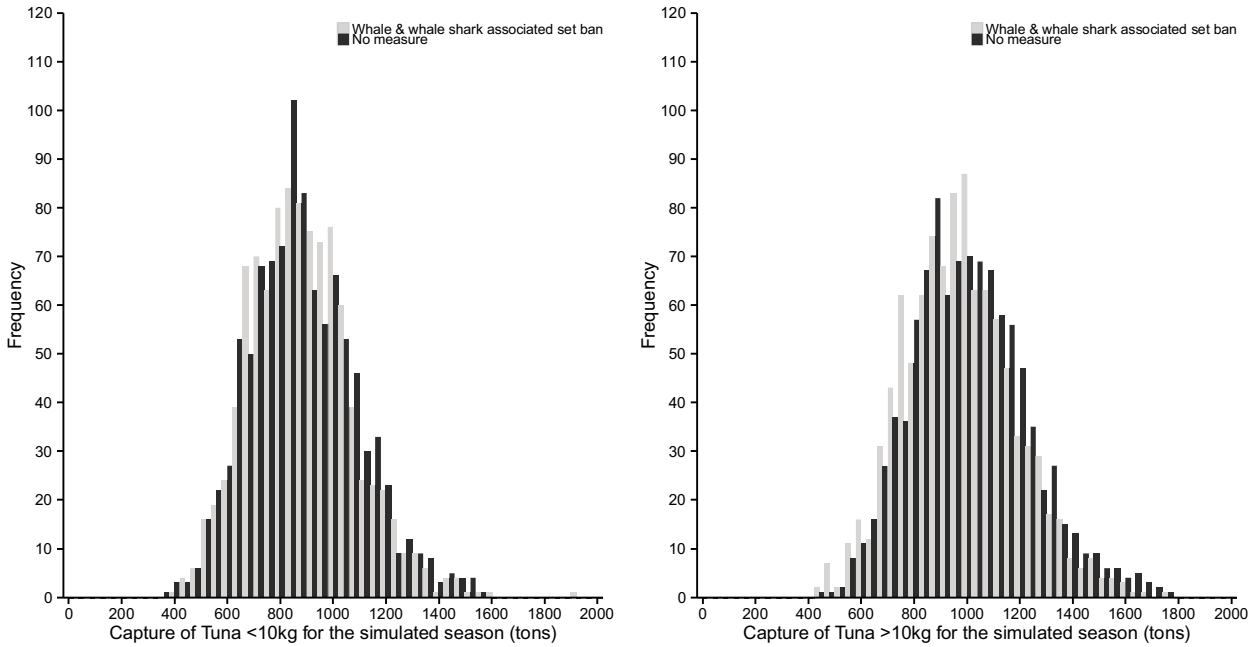

Figure 6.6 Simulated tuna catch by one French purse-seiner during season 3, for a moratorium on whale and whale shark associated sets in Cap Lopez, compared to the baseline.

6.4 Discussion

Two different approaches were used at fishery scale to i) evaluate the consequences of previous time-area regulations on FAD fishing and ii) evaluate the potential effects of bans on whale and whale shark associated sets. The first analysis showed that time-area regulation had varying but limited effects on the number of whale and whale shark associated sets. On the other hand, bans on these fishing modes, particularly when both were banned, produced changes in fishing strategies. An increase in the number of FAD and free school sets was

detected without any change in the tuna catch. However, there was a slight decrease in bycatch, such as chondrichthyans and billfishes.

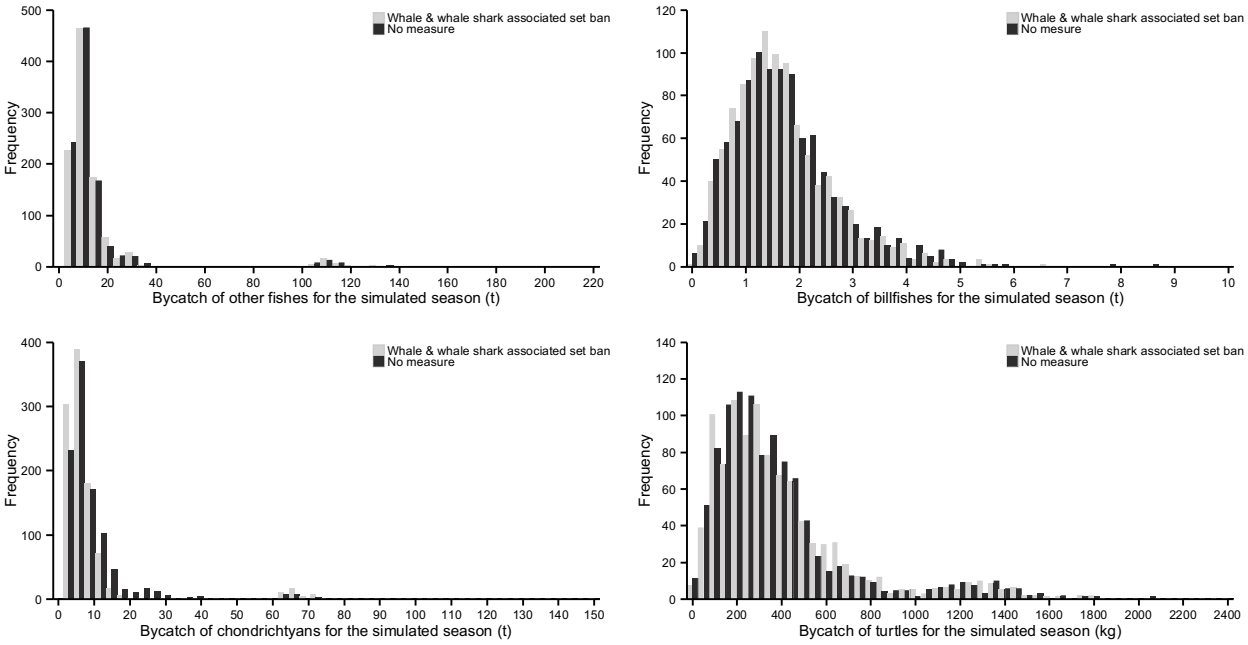

Figure 6.7 Simulated bycatch by one French purse-seiner during season 3, for a moratorium on whale and whale shark associated sets in Cap Lopez, compared to the baseline.

6.4.1 Past time-area regulations

The time-area regulations implemented in the EAO and WIO, as well as piracy, had varying effects on the number of whale and whale shark associated sets. It mainly depended on the ocean and the fishing mode considered. The lack of any reallocation of fishing effort to whale or whale shark associated sets in the EAO might be explained by the season when the moratoria on FADs were in place (November to January). This is a period with very few whale and whale shark associated sets. Indeed, these fishing modes are mainly undertaken from Capietto *et al.* 2014 Escalle *et al.* 2015). However, in the WIO, there was a slight decrease in i) whale and whale shark associated sets outside the area after the implementation of the Chagos no-take zone and ii) whale shark associated sets in the area where there was increasing piracy. This might be interpreted as a direct effect of the piracy threat. Fishermen will not spend any great length of time inside the piracy area searching for cues indicating the presence of tuna schools and will, therefore, also have fewer chances of setting on whale sharks. Indeed, whale sharks may be seen either before setting the net while searching for tuna schools. Conversely, and more usually, they may be observed only after setting the net on what first appeared to be a free swimming school. However, the slight decrease in both megafauna associated sets

in the whole WIO after the implementation of the Chagos no-take zone (2010-2014) may not necessarily be a result of this regulation. In September 2013, the IOTC prohibited the intentional setting of nets on whales and whale sharks (IOTC Res[13/04] and Res[13/05]). This restriction was particularly followed for whale shark associated sets. It led to 0 fishing sets recorded in 2013 and 2014 during the NE and ISW monsoon periods (i.e. the main seasons for whale and whale shark associated sets). In comparison, it reached an average 6.3). The same pattern was also shown for whale associated sets, with 50 sets in 2013 and 4 sets in 2014 during the same monsoon periods, compared to an average of 95 whale associated sets 6.3). This suggests that the decrease recorded during the period when the Chagos no-take zone was in force might in fact be due to this megafauna-specific conservation regulation. It is also possible that skippers did not declare whale and whale shark sets in their logbooks owing to the IOTC regulation. It could also mean that they might have changed their fishing behavior when scientific observers were onboard (i.e. avoiding whale or whale sharks, if possible). 100% coverage rate by scientific observers onboard purse-seiners is, therefore, required to confirm observations from logbook data.

The fishing effort regulations also had varying effects on the number of FAD and free school sets. They affected the fishing strategy and tuna catch of the European purse-seine fleet in the EAO and WIO. Overall, in the EAO, the moratoria on FADs, especially the first one, appeared to meet the main objective of decreasing the number of FAD sets to protect juveniles, with the fishing effort being mainly reallocated to free school sets. In the WIO, the main goal of the Chagos no-take zone, although not clearly defined, may be seen as a precautionary approach to protect the whole ecosystem and species present in this EEZ. Thus it did not directly aimed to conserve the stocks of tropical surface tuna, which are highly Kaplan *et al.* 2014). Reducing the European purse-seine fishing effort may, however, still be seen as a step towards this objective. Around the Somalia EEZ, various fishing effort regulations were in effect at the same period (risk of piracy all year round and no-take zone in November). This area is highly dominated by FAD fishing, especially from Fonteneau 2010). Our study showed that fishing effort regulations did not affect the number of whale or whale shark associated sets (except where there was an increase in piracy). It also underlined that fishermen reallocated their effort either to free schools or to FADs in other areas.

The results showed, firstly, in the EAO, during the first 3 month moratorium on FAD that there was a significant decrease in the number of FAD sets inside the area covered by 6.1 6.4). It did not completely stop the use of FAD sets Torres-

Irineo *et al.* 2011). The fishing effort was reallocated to free school sets, mostly outside the moratorium area. However, with this significant decrease, the moratorium still met its Torres-Irineo *et al.* 2011). To limit the non-respect of the moratorium, it was then replaced by a one month no-take zone in a small area of the EAO. However, it was not considered in this study as this regulation applied only for one month (November, a period with few whale or whale shark associated sets), and to a very small area.

Secondly, in the WIO, the study showed that the number of sets fell to almost 0 inside 6.1). However, outside this area, the effect varied depending on the fishing mode. Indeed, an increase occurred in the number of FAD sets and associated tuna catch, as well as a decrease in the number of free school sets. Results were similar for the period with increasing piracy activity: FAD sets increased outside the area with piracy 6.1). On the contrary, the number of free school sets and whale shark associated sets were already relatively low inside the area (4.3 and 0.1 sets per vessel per season, respectively). It decreased even further (1.7 and 0.0 sets per vessel per season). This may be explained by the fact that fishermen possibly still took the risk of entering the zone where there was a threat of piracy to complete FAD sets which could be located from a distance using satellite buoys. In addition, the size of the tuna school below the FADs could also be estimated from a distance with the echosounders that equipped it Chassot *et al.* 2010 Dagorn *et al.* 2013 Kaplan *et al.* 2014). They did not, however, spend time inside the piracy area searching for signs of the presence of free swimming tuna schools Kaplan *et al.* 2014). In addition they had fewer opportunities for whale shark associated sets, as already mentioned above. The two most recent regulations were introduced in 2012 and 2011: the Somalia no-take zone in the WIO and the second moratorium on FADs in the EAO, respectively. There were moderate changes in some absolute values of fishery indices. Indeed, the number of FAD sets decreased inside areas subject to both regulations, and increased outside the Somalia no-take zone. Although none of the differences were 6.1). This could be due to the fact that these regulations were recent (2 or 3 years), and had been in force for only one or two months. It resulted in very small sample sizes for the non parametric Wilcoxon statistical test (based on ranked values) used for comparison. Therefore, longer term study may be needed to quantify the effect of these regulations. It has also been suggested that the Somalia no-take zone may need to be Kaplan *et al.* 2014).

6.4.2 Simulation of fishing effort reallocation

This study set out to explore the consequences of restricting setting on whales or/and whale sharks. It was performed in light of the effects of previous time-area regulations, and considering that some conservation measures for megafauna species have already been taken (in the WIO). The Monte Carlo approach was used to model tropical purse-seiner fishing operations. It was implemented by estimating the potential transfer of the fishing effort to other fishing modes, and the related tuna catch and bycatch in areas and periods with higher whale and whale shark setting. Our findings showed that banning whale and/or whale shark associated sets would have little effect on tropical tuna purse-seine fishing, especially if the ban applied to one fishing mode for a specific region and season. Most of the time, there was a difference from the baseline only when sets on both whales and whale sharks were banned (e.g. in the EAO during season 3 in Cap Lopez for the French fleet and the whole of the 6.3 and 6.5 6.6 6.7). As these fishing modes represent only a small number of sets, a ban on only one fishing mode may not be expected to result in any significant difference from the baseline. This was, however, not the case for all scenarios. For instance, banning sets on whale sharks in the whole of the EAO during season 3 (Spanish fleet) were significantly 6.3). Likewise it occurred for banning sets on whales in the NE Seychelles sub-region during the NE and ISW monsoon periods (French fleet), and on whales or whale sharks in the whole of the WIO during the ISW monsoon period (both French 6.3). However, in some circumstances, a simulated time-area ban on whale or/and whale shark sets did not give significantly different result from the baseline. This may be because whale and whale shark associated sets represent only a small proportion of the fishing sets during the season considered. For the 1980–2004 period, the proportion of whale sets (up to 30% of all fishing sets during NE monsoon period in the WIO), and whale shark sets (up to 25% during season 2 in the EAO), were generally higher than during the 6.3). Consequently, the result of the simulations might have been different if older data had been used. However, this would not have reflected the current situation where bans have already been adopted, or it might be adopted in the future to protect these species.

In all cases where there was a significant difference between the baseline and a scenario with a ban on one type of fishing mode, the increase in the number of FAD and/or free school sets was due to the proportional reallocation of the sets of the banned fishing mode to the other fishing modes. A slight decrease in some groups of bycatch (chondrichthyans or billfishes) was also predicted. Furthermore, there was no evidence that tuna catches would

be affected by this type of regulation. This indicates that they may not lead to a decrease in the total tuna catch, although moratoria on setting on megafauna species may be restrictive for fishermen because they have to avoid some possible setting opportunities.

This study was based on several assumptions, which presented inherent limitations, Salas and Gaertner 2004 Fulton *et al.* 2011). They mainly dealt with the fishermen's behavior which is very difficult to predict. Monte Carlo simulations can propagate many uncertainties through the searching and fishing process characteristic of a fishing trip by a purse-seiner. However, we are aware that other uncertainties could have been included in the model. Firstly, in order to simplify the model, it was assumed that the simulated purse-seiner could not change the sub-region in which it was operating during a given fishing day. In addition, when a fishing mode was banned in a particular sub-region, the simulated vessel was not allowed to reallocate part of its effort to another sub-region (i.e. the fishing effort probability Pa was unchanged). Indeed, there was no simple, objective way of predicting where the fishing effort would have been reallocated. However, considering the large area covered by each sub-region, it is unlikely that a purse-seiner would change sub-region during a fishing day unless it was fishing close to the boundary between two sub-regions. Secondly, the number of fishing sets per day was not changed when a fishing mode was banned. The time spent by a purse-seiner to complete a whale or whale shark associated set is usually longer than for free school or FAD sets, especially for whale shark associated sets given the time taken to release the whale shark alive. However, this time could be used to search for another tuna school and make more fishing sets. Therefore, the potential number of fishing sets could increase. On the other hand, they could spend more time searching for tuna schools and so make fewer fishing sets in a given day. This can be the case if it is considered that fishermen have less opportunity to set nets because one or more fishing modes are banned. Therefore, as the simulation model was a simplistic approach, it was not possible to simulate a slight increase or decrease in the number of fishing sets (a number that was not an integer). Furthermore, the number of whale and whale shark associated sets per vessel was small (average of 2.3 ±0.3 and 2.8 ±0.3 whale associated sets and 1.3 ±0.2 and 0.9 ±0.1 whale shark associated sets per year per vessel, in the EAO and WIO, respectively, for the 2005–2014 period). Consequently, it was not possible to increase or decrease by 1 the number of fishing sets per day for a scenario including a ban. Thirdly, when a fishing mode was banned, it was considered that the probability of the occurrence of the remaining fishing modes was distributed proportionally (i.e. redistributed among the remaining fishing modes according to their respective probabilities). This may not represent what would happen in reality. Indeed, fishermen may focus preferentially mainly on one fishing mode, such as FAD sets, which in return may lead to an increase amount of

bycatch. Fourthly, in the tuna catch, all species of tuna were grouped into the same size categories because of the type of data used (i.e. non-corrected logbook, see Materials and Methods for details). Furthermore, account was not taken of the additional uncertainty. It was due to i) the annual variability in the data as this could not be easily included in the models, and ii) because the study focused mainly on seasonal patterns that occurred every year. In addition, it would have been relevant to validate the model using historical data. However the fishing strategies and spatial distribution in fishing effort have changed over time. This is especially the case when comparing the periods (i) before 2005 and (ii) during 2005–2014, which thus precluded such validation using historical data.

Finally, it should be stressed that bans on whale shark associated sets (i.e. intentional encirclement) may not be sufficient, although it have already been introduced in the WIO. Indeed, whale sharks are often not detected before setting and encirclement is often involun- Capietto *et al.* 2014). Consequently, in order to limit the effect of such encirclement by purse-seine nets, fishermen must be encouraged to use safe Escalle *et al.* in press). However, baleen whales are sighting cues used by fishermen to detect tuna schools at the surface of the sea. They remain associated with the tuna during the setting operation but usually manage to escape unaided during pursing (with a 94% apparent survival rate after Escalle *et al.* 2015). This being the case, skippers could easily comply with bans on whale associated sets, and providing that the number of scientific observers onboard fishing vessels is increased to 100% in both the EAO (implemented since 2014) and WIO.

6.5 Conclusion

Management and fishing effort regulations or conservation measures are generally introduced for a specific purpose. Account must be taken of the potential side effects that may arise as a result of these measures, especially considering the difficulty in predicting fishermen's behavior. Overall, in the EAO and WIO, the results of the before-after analysis of 1992–2014 data showed that implementing fishing effort regulations to reduce the effect of FAD fishing on tuna stocks had slight effect on the number of sets on megafauna species (concerning a FAD moratorium, a no-take zone, or piracy). Furthermore, the Monte Carlo simulation of whale shark and cetacean conservation measures predicted small but limited changes on the tuna catch and bycatch. In the WIO, intentional whale and whale shark associated sets are already banned. Based on logbook data, most fishermen comply with this restriction in the WIO, especially for whale sharks. However, this data must be confirmed by 100% coverage rate of scientific observers on board fishing vessels. In recent years, a

large proportion of the fishing effort has been concentrated on FAD sets, which raise some ecological concerns in terms of bycatch and tuna stock sustainability (Dagorn et al. 2013). With the increasing use of an ecosystem approach to fisheries, the consequences of more widespread regulations on FAD fishing (e.g. longer period of time, larger area, etc) should be assessed. These might lead to a major change in the fishing strategies regarding the fishing mode used and the spatio-temporal distribution of fishing effort.

Acknowledgements

We thank two anonymous Reviewers for their constructive comments on an earlier version of the manuscript. The authors are grateful to the skippers and fishing companies involved in the logbook data collection, which is supported by the French and Spanish National Fisheries Administrations and research institutes (IRD/IEO). We should also like to thank the teams of the "Observatoire Thonier" (IRD) and the "Centro Costero de Canarias" (IEO) for providing logbook data. L. Escalle is funded by a PhD grant from the University of Montpellier. T. Tebby has provided the English language editing for this paper.

Part 2. Forecasted consequences of FAD moratoria in the Atlantic and Indian Oceans on catches and bycatches.

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Published in ICES Journal of Marine Science (Article 7)

Escalle, L., Gaertner, D., Chavance, P., Delgado de Molina, A., Ariz, J., Mérigot, B. (In press) Forecasted consequences of FAD moratoria in the Atlantic and Indian Oceans on catches doi: 10.1093/icesjms/fsw187

Abstract

Given the increasingly extensive use of drifting Fish Aggregating Devices (FADs) by the purse-seine fisheries targeting tropical tunas, fishing effort restrictions have been introduced to manage tropical tuna stocks. However, these measures are focused on the protection of juvenile tunas and do not take account of the potential impact on bycatch or associated megafauna (whales and whale sharks). An iterative "fishing-day" Monte Carlo simulation model was developed to investigate the consequences on tropical tunas and bycatch of introducing extensive area six-month moratoria on FAD activities. The model allowed for variability in a range of plausible values of the parameters characterizing the fishing operations conducted by European purse-seiners in the eastern tropical Atlantic and western Indian Oceans for the period 2005–2014. Monte Carlo simulations, using probabilities based on these fishery data, were carried out for the French and Spanish fishing fleets separately to account for differences in fishing strategies. The models predicted a decrease in FAD sets and an increase in free school sets. As a consequence, the catch of small tuna (<10 kg) decreased while the catch of large tuna (≥10 kg) increased, leading to an overall increase in tuna catch of 100–200 t/yr/vessel in the Atlantic Ocean, and a decrease of 400–1500 t/yr/vessel in the Indian Ocean. The bycatch decreased in the Indian Ocean, while in the Atlantic Ocean in one hand billfishes, turtles and chondrichthyans bycatch increased slightly, and in the other hand other bony fishes decreased. Because fishing practices were modified, whale and whale shark associated sets increased slightly in the Indian Ocean. This study showed that simulations based on fishery data are a useful means of evaluating the trade-offs of time-area closures as part of an ecosystem approach to fisheries.

Keywords

Bycatch, ecosystem approach to fisheries, fish aggregating device, megafauna, Monte Carlo simulations, time-area restriction, tropical tuna purse-seine fishery.

6.6 Introduction

Tropical tuna stocks are exploited by a wide range of industrial and small-scale fisheries. Worldwide, these tuna stocks are considered to be fully exploited or subject to Juan-Jordá *et al.* 2011). This corresponds to the red quadrant of the Kobe plot commonly used by tuna Regional Fishery Management Organizations (tRFMOs) to summa- Kell 2011). Concerns about the sustainability of tropical tuna stocks have led to the implementation of time-area restriction covering one Harley and Suter 2007 Torres-Irineo *et al.* 2011 Kaplan *et al.* 2014).

Historically, tropical purse-seiners detected schools of tuna at the surface of the sea using visual cues, such as flocks of birds, disturbance on the surface of the water (e.g. breezers, foamers), natural floating objects (logs) or the presence of megafauna (whale sharks (*Rhincodon typus* Ariz and Gaertner 1999 Gaertner and Medina-Gaertner 1999 Hall *et al.* 1999 Hallier and Parajua 1999 Hampton and Bailey 1999). These visual cues continue to be used, although, since the early 1990s, fisheries have been taking advantage of the aggregative behavior of tuna around floating objects to facilitate their catch. Thus, artificial floating objects (e.g. bamboo rafts) have Ariz and Gaertner 1999 Hallier and Parajua 1999). These, and other floating objects, may be equipped with satellite linked echo-sounder buoys providing fishers with accurate position and rough estimates of fish Moreno *et al.* 2007 Lopez *et al.* 2014). These floating objects are classified as drifting Fish Aggregating Devices (FADs) and the corresponding setting is designated as a "FAD set". FAD sets and sets on free-swimming tuna schools (termed hereafter "free school set") are the main purse-seine fishing modes in the EAO and WIO.

In these oceans, free school sets (and whale associated sets) mainly catch large yellowfin tuna. FAD sets, on the other hand, catch mainly skipjack (*Katsuwonus pelamis*) as well as juvenile yellowfin and bigeye tuna (*Thunnus obesus*). FAD sets also have a much larger bycatch ratio than free school sets with a wider variety of species, including other bony fishes, billfishes, sharks (mainly silky sharks *Carcharhinus falciformis* Amandè *et al.* 2008 2010 Filmalter *et al.* 2013 Bourjea *et al.* 2014). The increasing use of FADs has thus raised some concerns on i) the recruitment of yellowfin and bigeye tunas, ii) the potential modifications of original behavior of tuna and non-tuna species (i.e. "ecological Marsac *et al.* 2000 Hallier and Gaertner 2008) and iii) a negative alteration of the Bromhead *et al.* 2003 Dagorn *et al.* 2013). Various measures to regulate the fishing effort, such as moratoria on FAD activities (i.e. ban

of all activities on FAD) or no-take zones (i.e. ban of all purse-seine fishing activities), have therefore been implemented by tRFMOs in both the EAO and WIO. They have principally been taken with the aim to protect juvenile yellowfin and bigeye tuna. In the EAO, the first moratorium on FAD activities, initiated on a voluntary basis by European purse-seiner vessel owner companies, was in force from 1997 to 2004 for three months (November to January) 6.8 and Appendix 6.A, ICCAT Rec [98-01] and [99-01]). As the moratorium was progressively not respected by some purse-seine fleets, a one month no-take zone was then introduced in 2004 over a more limited area (ICCAT [04-01]). A second moratorium on FADs in a different area of the EAO was introduced in 2012 and is still currently in place for two months (January and February; ICCAT [11-01] and [14-01]). In the WIO, a no-take zone was also introduced from 2011 to 2014 over a large 6.8

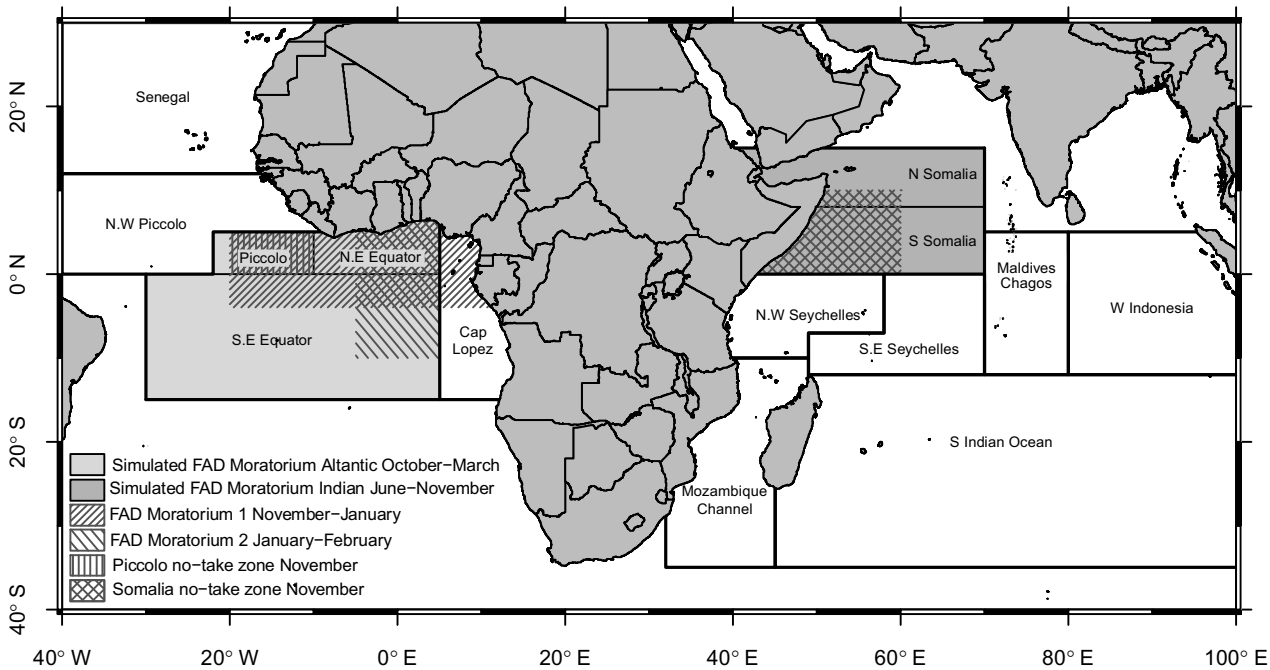


Figure 6.8 Sub-regions used by the European Union research institutes (IRD and IEO) for spatial sampling. Regions of the simulated six-month moratoria on FAD activities appear in light grey.

In the light of the restrictions that have already been introduced in both oceans

Torres-Irineo *et al.* 2011 Kaplan *et al.* 2014), the possibility of introducing more extensive moratoria has been suggested. This study set out to determine whether it is possible to use time-area moratoria over wider areas and for longer periods in order to i) meet the tRFMOs target of reducing the mortality of juvenile tuna while ii) meeting the Ecosystem Approach to Fisheries (EAF) aims of reducing the bycatch and iii) without increasing the impact on megafauna caused by the reallocation of effort from FAD sets to other fishing modes. The

effects of extensive moratoria on tuna catch and bycatch were explored using Monte Carlo simulation of the reallocation of the fishing effort. The reallocation was determined by selecting a path through the process potentially leading to a successful fishing set for each day of one fishing year based on the probabilities of the decisions made by fishers, tuna encounter rates and the fishing success.

6.7 Materials and methods

6.7.1 Data

Data were obtained from the logbooks of the European tropical tuna purse-seiners (France and Spain) and associated flagged vessels. This is the main surface fishing fleet (∼70% of the purse-seine tuna captured) operating in the EAO (since 1960s) and WIO (since 1980s), although Ghanaian and Seychelles purse-seiners, among others, also operate Fonteneau 2009 2010). Fishing activities (e.g. setting, moving between fishing areas, etc) have been systematically recorded by skippers since 1990 (90% coverage before this date). These are reported to the IRD for French vessels and the IEO for Spanish vessels. To give an up-to-date picture of the situation and strategies of European purse-seiners, including the last technological changes, we selected the logbook data for the last ten years (2005–2014). Each fishing set record includes i) the date and geographical location, ii) the cue, i.e. the association between the tuna school and floating objects (natural [1]), cetaceans, whale sharks, flocks of birds or free swimming tuna school and iii) the estimated catch of the set and the tuna species composition by commercial size category (< 10 kg, ≥ 10 kg). For data management purposes, the various fishing modes are then classified according to the cues for sighting the tuna school (FAD, free school, "whale associated sets" or "whale shark associated sets"). It should be noted that whale and whale shark associated sets are relatively rare events in both EAO and WIO (∼1.5% and ∼ Capietto *et al.* 2014 Escalle *et al.* 2015). In addition, their intentional setting has been banned in the WIO since 2013 (IOTC res. 13/03 and 13/05). On the basis of tuna species and size samples taken at landing sites, logbook data are corrected in order to reflect the tuna species composition per size category over Pallarés and Petit 1998). During this correction procedure, whale associated sets are combined with free school sets and whale shark associated sets with FAD sets. This corrected logbook dataset, useful for stock assessment purposes, was not used here because i) the data reported in logbooks are more representative in terms of commercial size

[1] In this study, when mentioning FAD, it includes both natural log and FAD.

category of the catch for each fishing set and ii) in the corrected dataset the four initial fishing modes are simplified to free school and FAD sets only. However as the tuna species may not be correctly identified in the logbooks, the tuna catch per size category was used without detailed consideration of species: tuna < 10kg (a mix of mostly skipjack tuna, juvenile yellowfin and bigeye tuna) and tuna ≥ [2].

Data from scientific observers onboard French purse-seiners were also used to assess the composition of the bycatch by large taxonomic groups. These data were collected by IRD from 2005 to 2014 as part of continuous data collection programs (i.e. the European Union Data Collection Framework; Regulation (EC) No 199/2008). The coverage rate over the period considered was about 23% of all fishing sets in the EAO (100% since 2014) and 12% in the WIO (50% since 2014). For each fishing set, the bycatch was identified by species, when possible, or else by taxonomic group (including discards of the target species). In this study, the bycatch was then assessed for each fishing set per taxonomic species group as follows: i) other bony fishes (all bony fishes except the targeted tunas species and billfishes), ii) billfishes, iii) chondrichthyans (sharks and rays) and iv) marine turtles.

6.7.2 Sub-regions and periods

The main fishing grounds of the European purse-seiners were divided into 6 sub- 6.8 Pallarés and Petit 1998) for spatial sampling.

Given the difference in the oceanography of the two oceans, the EAO was stratified into four quarters, starting from January and labeled 1 to 4, while the WIO being strongly affected by seasonal monsoons, was stratified into two main monsoon periods [north-east (NE) from December to March (1) and south-west (SW) from June to September (3)] and two inter-monsoon periods [south-west (ISW) in April–May (2) and north-east (INE) in Capietto *et al.* 2014 Escalle *et al.* 2015).

[2]Many commercial size categories are reported in logbooks. Skipjack tunas were entirely included in tuna < 10 kg. Most yellowfin and bigeye tuna categories were already corresponding to either < 10 kg or ≥ 10 kg. One category (yellowfin and bigeye tuna between 6 and 20kg) was however redistributed as follow: 20% in tuna < 10 kg and 80% in tuna ≥ 10 kg. Yellowfin and bigeye catch with size unknown category were removed.

6.7.3 Monte Carlo simulation

6.7.3.1. General principle

The strengths and weaknesses of a management regulation (i.e. time-area closure, moratorium) on a specific fishing practice can be evaluated by simulating the behavior-at-sea of the tuna purse-seiners. The model must include all the steps from selecting a fishing ground to the realization of the set in a decision process. However, the various fishing choices or risks (e.g. setting on a specific fishing mode, the success of the set) describing purse-seiner fishing operations are variable and difficult to quantify exactly, making it also difficult to predict the effect of a given regulation. In such context, Monte Carlo simulation can be used to propagate uncertainties in model inputs into uncertainties in model outputs. The uncertainties used as inputs are described using probability distributions, which define the range of values a variable may take (i.e. on the basis of historic data), and the probability of these values occurring.

Basically, Monte Carlo simulation, consists in drawing a large number of pseudo-random uniform variables (e.g. 1000) from the interval [0,1]. Then it assigns values less than or equal to the observed probability of an event (e.g. setting on a specific fishing mode, having a successful set (i.e. tuna caught)). For each simulation, all of the uncertain parameters were 6.4). The process was then repeated over time to calculate the outputs of the process after changing certain probabilities as a result of a restriction. This gave a large number of separate, independent outputs. Each represents one possible path that the process might follow over time. The outputs (e.g. total tuna catch per size category, total bycatch per taxonomic group, etc) were assembled into probability distributions of possible outcomes. As a result, the outputs of the model are not single values but probability distributions which can be used to calculate average values and corresponding confidence intervals. Monte Carlo methods have been used already to simulate the fishing strategies adopted by tuna fishermen Gaertner *et al.* 1996 Vaca-Rodríguez and Dreyfus-León 2000) and to estimate the amount Gaertner *et al.* 2002).

6.7.3.2. The iterative "fishing-day" model

Monte Carlo simulations were used to incorporate all known sources of uncertainty in the analysis of the potential effect of six-month FAD moratoria on tuna catch, bycatch and megafauna associated sets. This was done for one vessel during one year from a designated fleet (French or Spanish) in the EAO or WIO. French and Spanish purse-seiners

behave differently in terms of fishing modes and spatio-temporal effort distribution with high seasonal, annual and spatial variability in the fishing strategy. French purse-seiners mainly target free swimming schools (average of 69 and 45% in the EAO and WIO, against 28 and 52% for FAD sets). In contrast Spanish purse-seiners mainly set on FAD (47 and 67% in the EAO and WIO, against 52 and 34% for free schools). This difference may be explained by the fact that French crews are paid based on the value of the tuna catch (i.e. mostly targeting large tunas), while Spanish crews are mainly paid according to the tonnage captured (i.e.

6.9) allowed for random variation in 7 different conditional probabilities of the successive 6.4) that occurred for the vessel during each day: i) presence in 6.9), ii) change (or not) of sub-region given the moratorium 6.9), iii) the number of fishing 6.9), iv) the fishing mode for each 6.9 6.9), vi) the 6.9 6.9). These were based on probabilities that were calculated using commercial fishery data from European tuna purse-seiners (logbook or scientific observer data depending on the type of probability) over the 2005–2014 period. The probabilities used in the simulation are thus reflecting the current fishing strategies, distribution, tuna catch and bycatch of the French and Spanish fleets. Conditional probabilities were calculated for each sub-region (see 6.8), season (quarters in the EAO and monsoon or inter-monsoon periods in the WIO) and fleet (French or Spanish) and derived from cumulative probability 6.9 for histogram examples).

Table 6.4 Parameters and conditional probabilities used in the Monte Carlo simulations of six-month moratoria on FAD activities, derived from European purse-seine fishery data.

Symbol	Description
i	Index of day in a restricted fishing season.
I	Total number of days in a restricted fishing season: 90 days in the Atlantic Ocean, 60 or 120 in the Indian Ocean.
n1 to n6	Random numbers drawn and compared to the probabilities Pa, Pb, Pc, Pd, Pf and Pe.
q	Random number drawn and compared to the probability P_{stay} of staying in one of the sub-region of the moratorium during day i given the restriction.
j	Index of fishing set completed in day i.
J	Total number of sets j during day i (depends on Pb).
L	Any of the free access sub-region .
FM	Fishing mode: FAD, free school, whale associated, or whale shark associated.
C	Tuna catch (t) in size category c ($\leq$10 kg; >10 kg).
B	Bycatch (t) per taxonomic group. Note that an unsuccessful set (less than 1 t of tuna catch) may have a bycatch.
Pa_{reg}	Probability of fishing activity on day i in one of the sub-regions included in the moratorium on FAD activities[1].
Pa_L	Probability of fishing activity on day i in one of the unrestricted sub-regions L[1].
P_{stay}	Probability of staying in one of the sub-regions of the moratorium during day i given the restriction. P_{stay} = 0.21–0.82 in the Atlantic Ocean and 0.03–0.19 in the Indian Ocean, depending on the fleet, as well as each of the sub-region and period of the moratoria.
Pb	Probability of completing a given number of fishing sets (J) during day i, per sub-region[1]. Pb_0 represents the probability of 0 fishing sets. Pb_J represents the probability of J fishing sets.
Pc	Probability of each fishing mode FM: FAD, free school, whale associated, or whale shark associated set, per sub-region[1].
Pc'	Adjusted probability of each fishing mode FM. When FAD sets are banned, its probability of the occurrence is redistributed among the remaining fishing modes according to their probabilities.
Pd	Probability of successful fishing set, for each fishing mode and sub-region[1]. The set is either successful (tuna catch) or unsuccessful (less than 1 t of tuna catch).
Pe	Probability of catching C tons of tuna in the set for each fishing mode and sub-region. Two probabilities Pe_{C1} and Pe_{C2} are used for the two size categories: C1 tuna < 10kg and C2 tuna $\geq$10kg[1].
Pf	Probability of catching Bycatch-group B (B1 other fishes (t), B2 billfishes (t), B3 chondrichthyans (t), and B4 turtles (kg)), per fishing mode and sub-region[2]. To account for the presence of bycatch in unsuccessful tuna sets (< 1 t tuna catch), different probabilities were used for successful and unsuccessful sets (Pfp_{B1}, Pfp_{B2}, Pfp_{B3}, Pfp_{B4} and Pfn_{B1}, Pfn_{B2}, Pfn_{B3}, and Pfn_{B4}, respectively).

[1] Because fishing effort by regions and choices in fishing modes may differ in terms of proportion between both fleets, these probabilities were calculated from French and Spanish logbooks separately.

[2] The catch of bycatch by group, fishing modes and regions was assumed to be independent of the fishing fleet. Probabilities calculated using the French observers data.

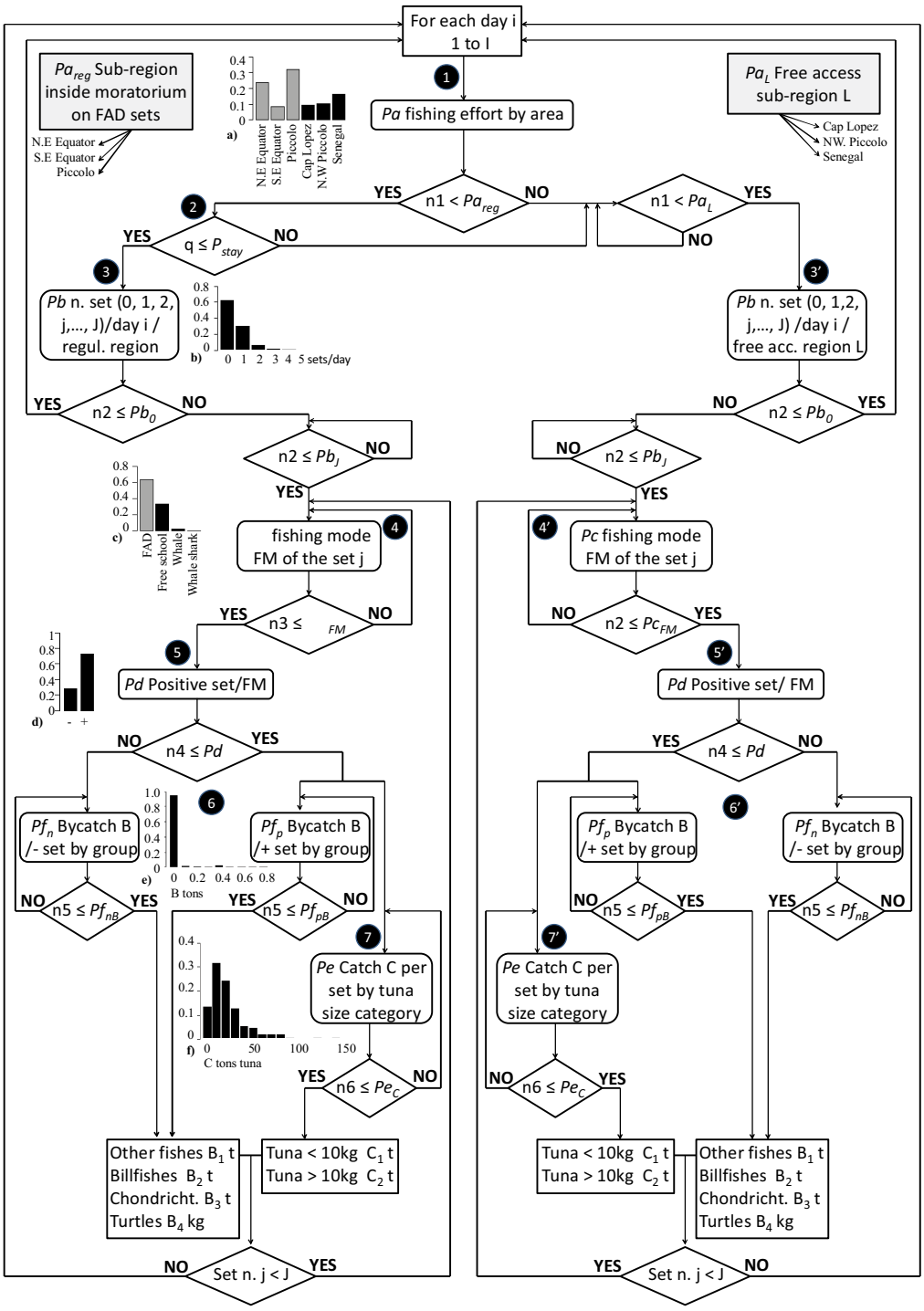


Figure 6.9 Representation of the decision process used for the Monte Carlo simulation. Histograms (illustrative only, as for the simulation cumulative histograms have been used) given as examples, are probabilities of a) fishing in each sub-region during season 4 in the Atlantic Ocean (*Pa*), b) number of fishing set per day in N.E Equator (*Pb* N.E Equator), c) fishing mode when there is no Moratorium on FAD (*Pc*), d) free school set successful or not (*Pd* free school set), e) bycatch of other bony fishes in a free school set (*Pf* other bony fishes/ free school set), f) catch of tuna ≥10kg in a free school set (*Pe* tuna ≥10kg/ free school set). n (n1, n2 . . .) and q are the random numbers drawn and compared to each probability. Rounded rectangles were used for probabilities description. Diamonds boxes represent the comparison between random numbers and probabilities. Rectangles were used for information or model outputs.

6.7.3.3. Areas and period considered

In order to simulate the potential impact of six-month large FAD moratoria, various scenarios, based on historical data from the European tuna purse-seine fishery were used as 6.8) and periods considered for the simulated 6.10 6.11). This was chosen in order to be able to compare the consequences between the existing time-area FAD moratoria and the larger and longer ones simulated. In the EAO, the simulated FAD moratorium covered the Piccolo, NE Equator and SE equator sub-regions during seasons 6.8 6.10 6.11), where FAD sets accounted for 37.3% ±14.0 of the sets for the French fleet and 65.0% ± [3]. In the WIO, it covered the N Somalia and S Somalia sub-regions during the SW and INE monsoon 6.8 6.10 6.11), for which FAD sets accounted for 86.7% ±17.7 of the sets for the French fleet and 90.9% ±7.0 for the Spanish fleet3. In order to model a purse-seiner's behavior, during the moratoria period, the fishing effort could be reallocated to areas where any fishing mode was allowed. This meant that if a purse-seiner would normally fish in a sub-region subject to restrictions it could move to another sub-region. Given the proportion of FAD sets mentioned above, it was taken that this would occur in 0.18–0.79% and 0.81–0.97% of the cases in the EAO and WIO, respectively, depending on the fleet, sub-region and season considered (*Pstay* 6.4). Two scenarios were tested for each ocean and fleet. In scenario 1 each purse-seiner may reallocate its fishing effort to any of the unrestricted sub-regions depending on its probability of being present in the sub-region considered (*Pa*). In scenario 2 (the "fishing the line scenario"; Kellner et al., 2007), the purse-seiner reallocated its fishing effort only to adjacent sub-regions, depending on the probability of being present. In such scenario, in the case of the EAO the simulated vessel may only transfer its fishing effort to N.W Piccolo and Cap Lopez. In the WIO the 6.8). The adjacent Maldives-Chagos sub-region was not included, considering the low fishing effort observed in the fishery data (<0.5% of the fishing days).

[3]average of 11 French and 31 Spanish operating purse-seiners per year in the EAO; and 17 and 25 in the WIO.

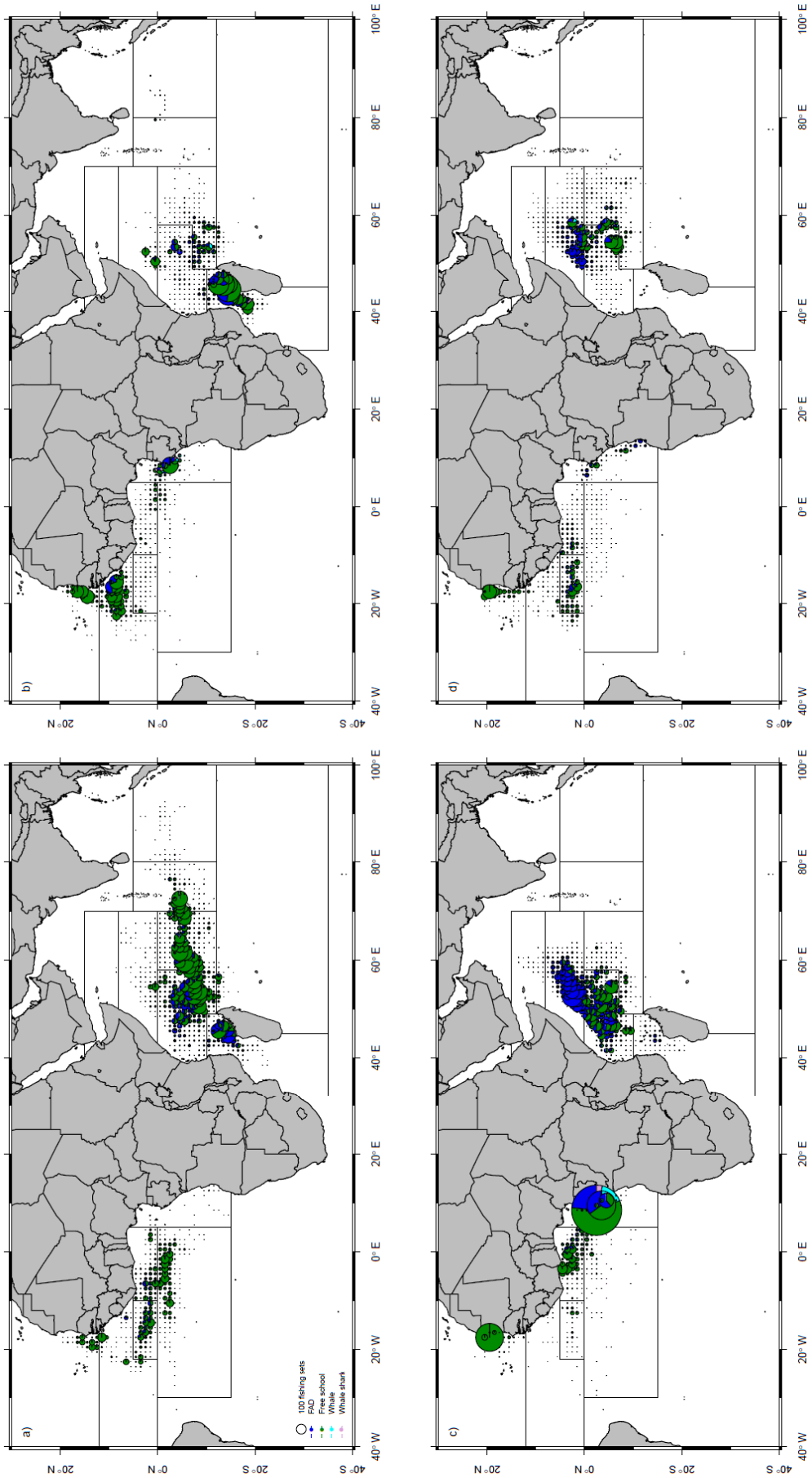


Figure 6.10 Map of seasonal number of fishing sets per fishing modes of the French purse-seine fleet for the 2005–2014 period. a) Season 1 and NE monsoon period, b) season 2 and ISW monsoon period, c) season 3 and SW monsoon period, and d) season 4 and INE monsoon period.

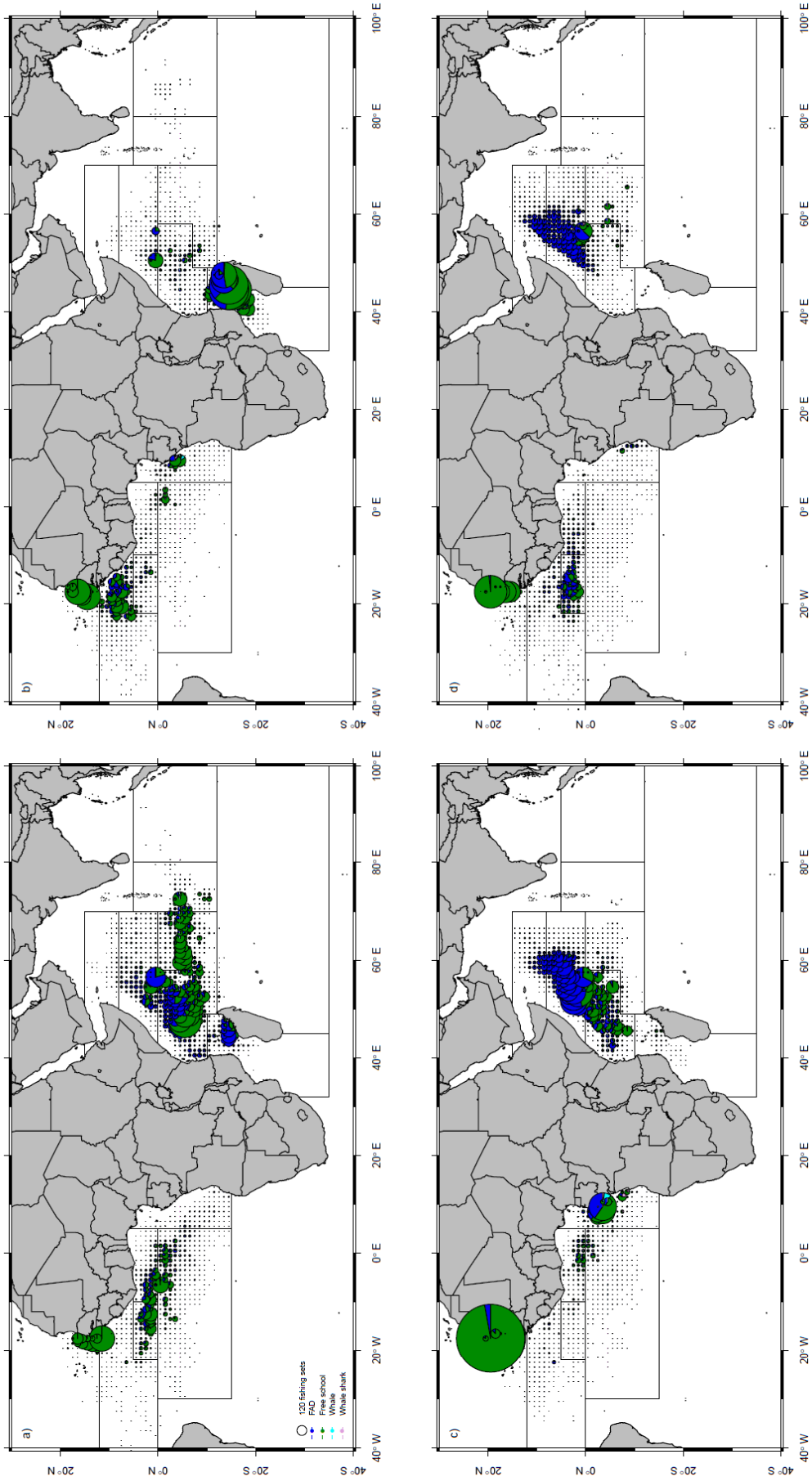


Figure 6.11 Map of seasonal number of fishing sets per fishing modes of the Spanish purse-seine fleet for the 2005–2014 period. a) Season 1 and NE monsoon period, b) season 2 and ISW monsoon period, c) season 3 and SW monsoon period, and d) season 4 and INE monsoon period.

6.7.3.4. Simulating six-month moratoria on FAD activities

As this study set out to detect the effects of potential six-month FAD moratoria, a simulation, based on the real fishery data, without any ban was tested to provide a baseline. This first simulation would reflect the global current situation of the fishery over the 2005–2014 period (i.e. including the fishing effort restrictions already established by tRFMOs). The two scenarios previously mentioned were then separately simulated for the FAD moratorium defined for each ocean. The major difference from the baseline scenario was that, when a moratorium was simulated, the probability of the occurrence of a FAD set inside the restricted area was redistributed among the remaining fishing modes in proportion to their respective probabilities (the probability *Pc* of setting on a specific fishing mode in the restricted sub-region becoming *Pc'* 6.4).

Each Monte Carlo simulation (i.e. the baseline and the two scenarios) was carried out 1000 times for one fishing year (i.e. average number of fishing days per vessel for each fleet and ocean in the fishery data) of one vessel from a designated European fleet. Each day i of the year, the vessel may fish in any of the sub-regions with each probability varying depending on the season. For each day i, a random number (n1) was drawn and compared to the probability *Pa* 6.9). The vessel was then assumed to spend the day in one of the restricted sub-regions or in one of the free-access sub-regions (left and right section, 6.9). If the vessel was assumed to spend the day i in a restricted sub-region, a random number q was drawn and compared to the probability of staying in this sub-region P_{stay} 6.4 6.9). If $q \leq P_{stay}$ the vessel would stay in the sub-region and the process would go to step 3, otherwise another number n1 was drawn and compared to the probability Pa_L with only the unrestricted sub-regions to determine where the fishing effort is reallocated. Then a number n2 was generated at random and compared to the probability *Pb* of having j fishing sets (0 to 5 in the EAO and 0 to 6 in the 6.9). If 0 fishing set was drawn, then the simulation 6.9), otherwise j fishing sets were simulated successively. The same process was repeated to determine the fishing mode associated with each set j (n3 vs *Pc* 6.9) and whether the set for this fishing mode was successful or not (n4 vs *Pd* 6.9). To characterize the uncertainty in the catch of tuna, as well as in the bycatch, 4 random numbers n5 were generated for all cases (fishing set successful or not, as it was assumed that an unsuccessful 6.9) and compared to the probabilities *Pfn* or *Pfp* of having B t of bycatch per species group. If the set was successful, 2 new random numbers were generated and compared to the probabilities *Pe* of having C t of tuna caught per size

6.9).

In order to facilitate the comparison between oceans and fleets, the results in terms of i) number of set per fishing mode, ii) tuna catch for each size category and iii) bycatch per species group, were calculated on a vessel basis and by year for all sub-regions taken together. The statistical difference between the two simulated Monte Carlo distributions was then tested using a Kolmogorov-Smirnov test. All the analyses were conducted using R software v.3.0.2 (R Development Core Team 2014).

6.8 Results

The simulation of a six-month moratorium in the EAO and WIO gave different results depending on the parameter considered (i.e. number of set, catch, bycatch), as well as on 6.5). Overall, the results showed a decrease in FAD sets and an increase in free school sets in both oceans. The resulting total tuna catch decreased in the WIO, but increased in the EAO. In the WIO only, there was also an increase in some megafauna associated sets. There were contrasted results for the bycatch depending on the species group, the ocean and the fleet.

Table 6.5 Results of Monte Carlo simulations of six-month moratoria on FAD activities in specific area and period of the eastern Atlantic (EAO) and western Indian Oceans (WIO). For each simulation, the fishery indices are given as an average per year and vessel for the baseline simulation (BL, i.e. current situation without the simulated moratorium), then as the difference between this value and the average of the parameter for each scenario of a simulated FAD moratorium.

Oc.	Fl.	Period of the moratorium	Sc.	FAD	FrSc	WHA	WHS	Tuna < 10kg (t)	Tuna ≥ 10kg (t)	Total tuna catch (t)	Fishes (t)	Billfishes (t)	Sharks (t)	Turtles (kg)
EAO	FR		BL	54.1	131.8	4.6	1.7	1922.3	2417.6	4339.9	17.1	8.9	**6.5**	395.8
		1 and 4	1	**- 13.8**	**+ 21.7**	*+ 0.1*	*+ 0.0*	**- 56.8**	**+ 160.9**	**+ 104.1**	**- 4.3**	*+ 0.1*	**+ 1.1**	**+ 47.7**
		1 and 4	2	**- 8.1**	**+ 15.6**	*+ 0.2*	*+ 0.1*	**- 14.3**	**+ 228.3**	**+ 214.0**	**- 2.0**	**+ 0.4**	**+ 1.5**	**+ 110.2**
	SP		BL	84.1	94.2	1.3	1.3	3196.3	2828.0	6024.3	24.2	4.6	5.0	239.1
		1 and 4	1	**- 12.9**	**+ 20.2**	*+ 0.1*	*0.0*	**- 316.8**	**+ 479.2**	**+ 162.4**	**- 3.5**	*0.0*	**+ 1.0**	**+ 59.6**
		1 and 4	2	**- 4.5**	**+12.8**	*+ 0.1*	*0.0*	**- 67.0**	**+ 284.1**	**+ 217.1**	*+ 0.2*	**+ 0.3**	**+ 1.5**	**+ 99.1**
WIO	FR		BL	118.2	98.3	6.0	1.0	3308.4	2575.7	5884.1	100.8	9.1	18.0	104.8
		SW and INE	1	**- 21.4**	**+ 13.1**	**+ 0.6**	*+ 0.1*	**- 641.6**	**+ 253.5**	**- 388.1**	**- 11.7**	**- 0.7**	**- 3.1**	**- 21.3**
		SW and INE	2	**- 21.2**	**+ 12.5**	**+ 0.8**	*+ 0.1*	**- 628.5**	**+ 259.9**	**- 368.6**	**- 13.1**	**- 0.3**	**- 3.1**	**- 21.8**
	SP		BL	155.8	91.8	0.7	0.9	6509.9	2799.9	9309.8	135.8	9.7	25.2	110.4
		SW and INE	1	**- 26.6**	**+ 13.2**	*0.0*	*+ 0.1*	**- 1707.4**	**+ 151.9**	**- 1555.5**	**- 16.8**	**- 0.1**	**- 6.3**	**- 18.8**
		SW and INE	2	**- 25.8**	**+ 12.3**	*+ 0.1*	**+ 0.2**	**- 1686.8**	**+ 176.7**	**- 1510.1**	**- 15.4**	**- 0.6**	**- 6.3**	**- 14.3**

Oc.= Ocean, Fl.= Fleet, Sc.= Scenario, SW= south-west monsoon, INE= intermediate north-east monsoon. FAD= Fish Aggregating Device set, FrSc= Free school set. WHA= Whale associated set, WHS= whale shark associated set. Bold font represents significant increase or decrease and italic no significant difference of the fishery index from the baseline (based on Kolmogorov-Smirnov tests).

Firstly, for the two main fishing modes, FAD and free school sets, the simulation of a six-month FAD moratorium gave similar predictions for all combinations of scenario,

ocean and fleet. The highest decrease in FAD sets would be in the WIO for the Spanish fleet, from an average of 155.8 FAD sets/yr/vessel to 134.2 sets/yr/vessel. The highest increase in number of free school sets would be in the EAO for the French fleet, from an average 6.5 6.12 6.13). The

6.5 6.12). In the WIO, the number of whale associated sets would increase by ∼0.6–0.8 set/yr/vessel for the French fleet and the number of whale shark associated sets 6.5 6.13).

Secondly, for the tuna catch, the predictions were similar between fleets but differed 6.5 6.12 6.13). In the EAO, small tuna catch (< 10 kg) would decrease by 14–57 t/yr/vessel for the French fleet and by 67–317 t/yr/vessel for the Spanish fleet. On the contrary, large tuna catch (≥ 10 kg) would increase by 161–228 t/yr/vessel for the French fleet and by 284–479 t/yr/vessel for the Spanish fleet. Therefore, the total tuna catch would increase for both fleets by 104–217 t/yr/vessel. In the WIO, similar predictions were found for the tuna catch by category: small tuna catch would decrease (629–642 and 1687–1707 t/yr/vessel for the French and Spanish fleets, respectively), and large tuna catch would increase (254–260 and 152–177 t/yr/vessel for the French and Spanish fleets, respectively). However here the total tuna catch would decrease by 369–388 t/yr/vessel for the French fleet and by 1510–1555 t/yr/vessel for the Spanish fleet.

Finally, the results were variable for the different bycatch groups. The bycatch of other bony fishes and billfishes would mainly decrease in both oceans, as would the bycatch of chondrichthyans and turtles in the WIO while increasing in the EAO. Looking in further details for each group, the bycatch of other bony fishes would decrease, for all cases, by 0–16.8 6.5 6.12 6.13). Billfishes bycatch would also decrease in the WIO (by 0.1–0.7 t/yr/vessel) but would be stable or increase slightly in the EAO (+ 0.3–0.4 t/yr/vessel). Chondrichthyans bycatch would increase in the EAO (by 1.0–1.5 t/yr/vessel) but would decrease in the WIO (by 3.1 and 6.3 t/yr/vessel for the French and Spanish fleets, respectively). Similarly, the bycatch of turtles would increase in the EAO (by 47.7–110.2 kg/yr/vessel) and decrease in the WIO (by 21.3–21.8 and 14.3–18.8 kg/yr/vessel for the French and Spanish fleets, respectively).

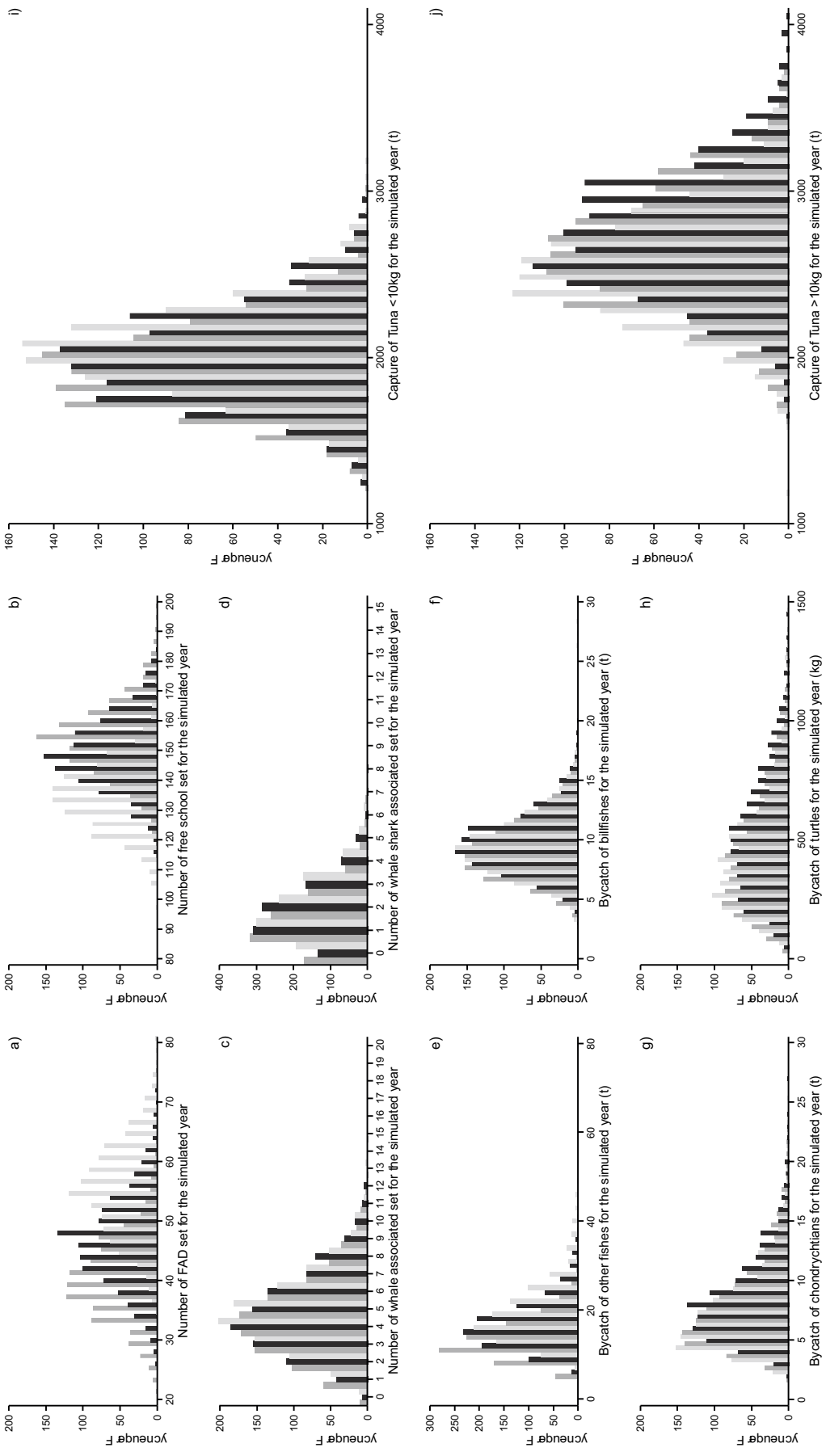


Figure 6.12 Simulated fishery indices: a) FAD set, b) free school set, c) whale associated set, d) whale shark associated set, e) bycatch of other bony fishes, f) bycatch of billfishes, g) bycatch of chondrichthyans, h) bycatch of turtles, i) catch of tuna < 10 kg and j) catch of tuna $\geq$ 10 kg, for one French purse-seiner over one fishing year with a moratorium on FAD during season 1 and 4 (dark grey = scenario 1; black = scenario 2) in the Atlantic Ocean, compared to the baseline (light grey).

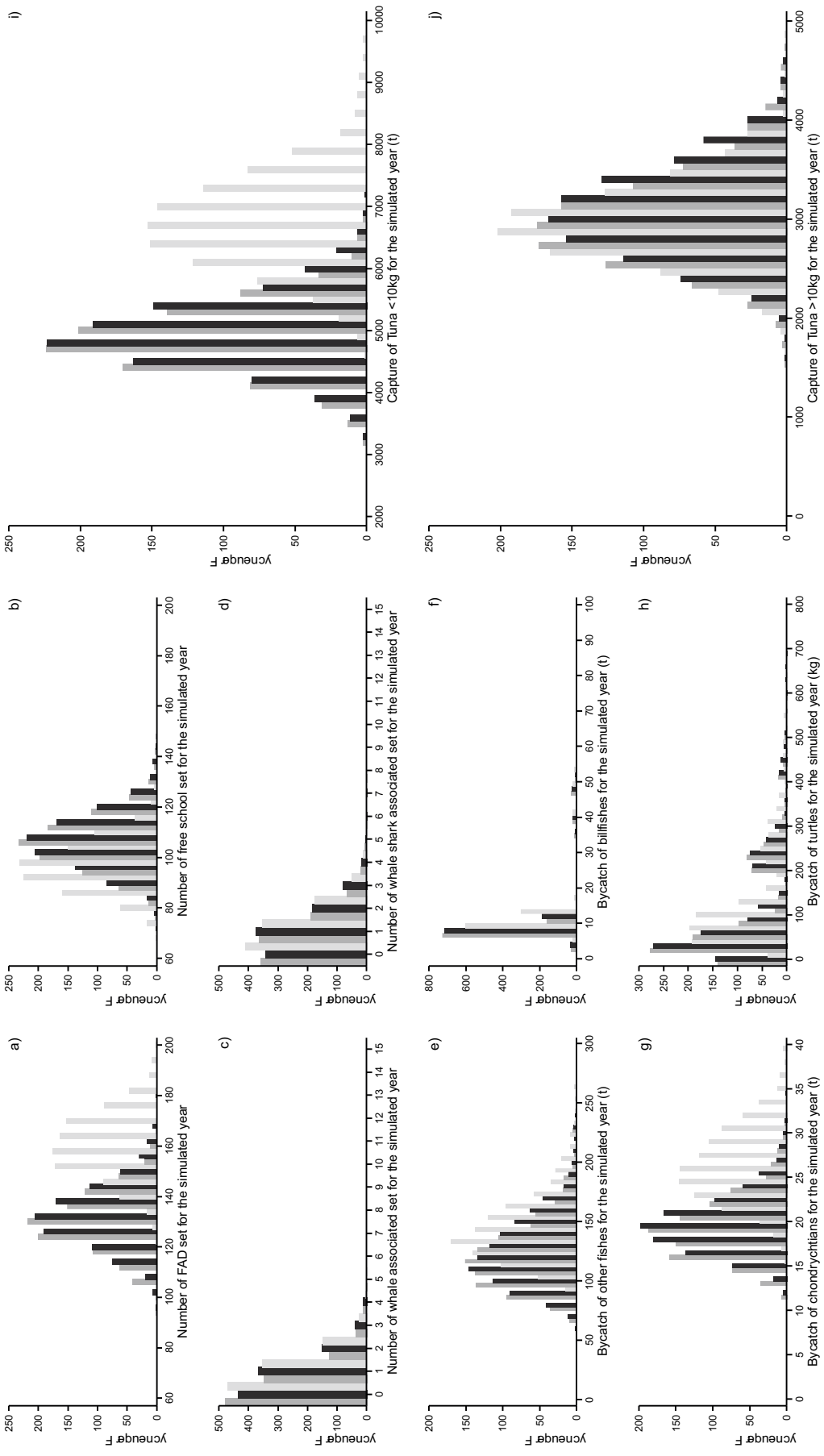


Figure 6.13 Simulated fishery indices: a) FAD set, b) free school set, c) whale associated set, d) whale shark associated set, e) bycatch of other bony fishes, f) bycatch of billfishes, g) bycatch of chondrichthyans, h) bycatch of turtles, i) catch of tuna < 10 kg and j) catch of tuna $\geq$ 10 kg, for one Spanish purse-seiner over one fishing year with a moratorium on FAD during SW and INE monsoon periods (dark grey = scenario 1; black = scenario 2) in the Indian Ocean, compared to the baseline (light grey).

6.9 Discussion

It is commonly accepted that fisheries have a direct impact on the whole marine ecosystem and for this reason the EAF is being promoted as a framework for sustainable development, recognizing the interdependence between human well-being and ecosystem Garcia *et al.* 2003). However, although this principle is generally accepted and some Juan-Jordá *et al.* 2015a), the types of action needed to set up EAF management plans are still not set up by tRFMOs. For various reasons (lack of time, lack of data for non-targeted species), the multi-annual management plans adopted by tRFMOs, even with the recent application of the Management Strategy Evaluation (MSE), have had a very limited scope. For instance, the focus has been on the risk of the spawning-stock biomass (SSB) of the targeted tuna species falling below the level at which recruitment is likely to be impaired. Several time-areas fishing effort regulation measures have thus been implemented. However, there has been little, if any, consideration of the ecological impact of these fishing restrictions, specifically for non-target species.

Monte Carlo simulations were used in this study to evaluate the consequences of wide-area FAD moratoria on tuna resources, as well as on the main groups of bycatch species and megafauna associated with purse-seine fishery. This approach was used as the multiple uncertainties can propagate through the searching and fishing processes characteristic of a fishing trip by a purse-seiner. However, some limitations were not accounted for in the simulation process, for instance i) the annual variability of the data could not be easily included in the models, ii) the catch of all tuna species were grouped into the same size categories because of the type of data used (i.e. non-corrected logbooks, see Materials and Methods for details), iii) while some bycatch species have different biology and ecology (e.g. marlins and sailfishes, sharks and rays) and some vulnerable species may benefit having a special focus (e.g. silky sharks, manta rays), bycatch species were grouped into four categories in order to give a general picture of the whole epipelagic ecosystem, and iv) each purse-seiner could operate in only one sub-region in a given day. Some fishery factors could also not be accounted for in the simulations (e.g. use of supply vessels, limitation in the [4]), as well as future fisher's behavior-at-sea in response of extended time-area moratoria. It addition, it would have been useful to have been able to validate the model, for example using historical data. However, as fishing strategies and spatial distribution in fishing effort have changed over time, particularly between the periods 1980–2004 and 2005–2014, the use of data covering a period before 2005 to validate

[4]See European Research Project Catch, Effort, and eCOsystem impacts of FAD-fishing (CECOFAD) for details.

the model would not have been appropriate.

In the EAO and WIO, FAD sets generally capture more tuna < 10 kg, mainly adult skipjack with juvenile yellowfin and bigeye tunas, as well as a greater bycatch, than free school sets. Wide area FAD moratoria could, therefore, be introduced in the future in order to protect juveniles of tropical tuna, but also limit the impact of purse-seine fishery by reducing the bycatch of endangered species. As expected, owing to the characteristics of the time-area strata selected for the FAD moratoria, the results of the iterative "fishing-day" model showed a decrease in the number of FAD sets. This was partially or totally balanced, depending on the ocean, by an increase in the number of free school sets. Indeed the overall number of sets increased in the EAO but decreased in the WIO. Consequently the catch of tuna < 10 kg generally decreased while the catch of tuna ≥ 10 kg increased. In the WIO, both scenarios were equivalent, with the fishing effort mainly reallocated to areas adjacent to the moratorium (see Appendix 6.C and 6.D as supplementary material). This is a well known Kellner *et al.* 2007 Torres-Irineo *et al.* 2011). It was however not the case in the EAO, where the number of free school sets highly increased (+13 sets for each fleet) in the Senegal sub-region (Appendix 6.H). This sub-region was Fonteneau *et al.* 2000a). This may thus explain the high difference in the capture of tuna catch per category between oceans.

While the trend of tuna catch per commercial category was the same, the consequences of the simulated moratoria on the overall tuna catch varied between oceans. At the scale of the fishery, catch could increase up to 2500 and 8000 t/yr in the EAO and decrease up to 6500 and 39,000 t/yr in the WIO, for the French and Spanish fleets, respectively. Therefore, the net loss in tuna catch could be particularly serious for the Spanish fleet, where FAD sets, during the period of the simulated moratorium, accounted for 36% of their total yearly catch. It should be mentioned that the price of the species and size categories of tuna should be kept in mind. Large tunas have higher commercial values than smaller ones, even if high fluctuations have occurred and the price differential between small and large tuna may affect the choice of future fishing strategies (free school vs. FAD).

The main reason for the implementation of more extensive time-area restrictions on FAD sets is to limit the capture of juvenile tuna but the reduction of bycatch appears as a reasonable secondary objective. This second objective would be fully achieved in the WIO, where all groups of bycatch would decrease. In the EAO the bycatch of other bony fishes, which represent a large proportion of the bycatch on FAD sets would also decrease 6.5 6.12 6.13). The bycatch of billfishes would however remain relatively stable in this Ocean (or slightly increase). A previous study using French and Spanish

observer data found that the introduction of a FAD moratorium led to a significant decrease in the catch of marlins, which are mainly captured on FAD sets. At the same time it also

Gaertner *et al.* 2002). Therefore the pattern observed in the bycatch of billfishes in the EAO, may be explained by the same phenomenon. Further details in the species captured would allow a more comprehensive vision of the pattern of billfishes bycatch during the simulated moratorium. The capture of chondrichthyans and turtles increased in the EAO. Turtle bycatch is more widespread in both free school and FAD sets in the EAO than in the Amandè *et al.* 2010 2012 Bourjea *et al.* 2014). The chondrichthyans bycatch, mainly constituted by silky sharks, is higher, in both oceans, in FAD sets than in free school sets. The main area for silky shark bycatch in the WIO is within the area covered by the simulated moratorium (N and S Somalia). In the EAO however the main shark (of all species) bycatch areas are off Mauritania and Cape Lopez in the EAO, which are not part of the moratorium area Torres-Irineo *et al.* 2014). Therefore, the reallocation of the fishing effort to unrestricted areas, with higher chondrichthyans bycatch in both free school and FAD sets might explain the increase predicted in the EAO. Conversely, the reallocation of the fishing effort away from areas with high chondrichthyans bycatch might explain the decrease predicted in the WIO. In addition, it must be stressed that manta rays are sometimes caught in free school sets and mostly in Cape Lopez and Piccolo NW sub-regions, but this is rare compared to the capture of silky sharks.

This study assessed the effects of time-area closures for FAD activities. However, more than one restriction may be in force at any one time. In the WIO, the IOTC has banned intentional sets on whales and whale sharks since 2013 (IOTC res. 13/03 and 13/05). This does not appear in our data as the whole 2005–2014 period was considered. However, the study predicted that a six-month FAD moratorium in the WIO would lead to a slight increase in whale and whale shark associated sets. At fishery scale, this would represent 116 whale associated sets per year (100 sets without the moratorium for the French fleet only) and 92 whale shark associated sets (80 sets without the moratorium for the French and Spanish fleets). Full observer coverage has not yet being achieved in the WIO owing to the lack of space onboard the purse-seiners (armed guards onboard to prevent piracy). While electronic observers (onboard video camera) are currently tested, the lack of full observer coverage may lead to under report or fail to report megafauna associated sets by skippers, which could, as simulated, reallocate fishing effort toward these fishing modes.

The current time-area closure in the WIO (IOTC res. 12/13), has already proved Kaplan *et al.*,

2014). Our study showed that a more extensive six-month restriction on FAD activities would limit the catch of small tuna (skipjack and juveniles) and reduce the bycatch of all groups of species, including endangered species such as sharks and turtles. In the EAO, the moratorium tested, like previous ones, would not completely fulfill its objectives. While the number of FAD sets is lower in the EAO, it is more widespread in space compared to the WIO. Therefore, more flexible restrictions could be considered in the EAO. For instance, spatio-temporal bans taking into account FAD fishing, as well as shark and turtle bycatch hotspots could be investigated. A dynamic management measure based on the main FAD fishing areas each year could also be considered. This would however be very difficult to implement in this ocean wide and international fishery. A more restrictive FAD limitation per purse-seiner in the whole EAO could also be considered. Recently, ICCAT (Rec [15-01]) and IOTC (res. 15/08) have adopted the limitation of 500 and 550 active FAD buoys, respectively, per purse-seiner at any time, which is above the previous French vessel owner one of 150 Goujon *et al.* 2015).

6.10 Conclusion

Monte Carlo simulations were carried out to examine various scenarios for reallocating spatially the fishing effort or changing fishing practices (i.e. fishing mode) following the introduction of a six-month FAD moratorium. The simple iterative "fishing-day" model took account of the probability of the occurrence of several different fishing events and skippers' on-the-spot decisions based on European purse-seine fishery data from the period 2005–2014. However, this approach is by definition unable to take account of the uncertainty associated with the skippers' behavior-at-sea in the future. While allowing for this limitation, this study gave an insight into the trade-off between the advantages and disadvantages of extensive time-area closures in the EAO and WIO in an EAF framework. The results showed that the objectives of such measures would be achieved in the WIO, with a significant reduction in the capture of small tuna (the actual reduction in the juvenile tuna catch needs to be evaluated), as well as a decrease in all bycatch groups. In the EAO, while the catch of small tuna decreases, results were contrasted for bycatch indicating that different type of complementary measures should be investigated. By assessing the effect of restrictions on both the target and bycatch species, and, therefore, the whole community that might be affected by the purse-seine fishery, this study argues in favor of adopting an ecosystem approach to fisheries.

Acknowledgements

We thank two anonymous Reviewers for their constructive comments on an earlier version of the manuscript. The authors are grateful to the skippers, fishing companies and observers onboard involved in the logbook data collection and observer programs, which are supported by the French and Spanish National Fisheries Administrations and research institutes (IRD/IEO) within the framework of the EU DCF. We would also like to thank the teams of the "Observatoire Thonier" (IRD) and the "Centro Costero de Canarias" (IEO) for providing logbook and observer data. The first author (L. Escalle) is funded by a PhD grant from the University of Montpellier. This study is part of the European Research Project Catch, Effort, and eCOsystem impacts of FAD-fishing (CECOFAD).

Appendix 6.A

Fishing effort regulations introduced and simulated in the Atlantic and Indian Oceans.

Ocean	Regulation	Area	Approximate size (km^2)	Year	Period
Atlantic	Moratorium on FAD	4°S–5°N 20°W–African Coast	∼3 500 000	1997–2004	November to January
	No-take zone	0–5°N 20–10°W	∼600 000	2004–2011	November
	Moratorium on FAD	10°S–African Coast 5°W–5°E	∼2 000 000	2012–2014	January to February
	Simulated Moratorium on FAD	Piccolo, N.E Equator and S.E Equator sub-regions	∼8 500 000		October to March
Indian	No-take zone	0–10°N 40–60°E	∼1 500 000	2010–2014	November
	Simulated Moratorium on FAD	N. Somalia and S. Somalia sub-regions	∼5 500 000		June to November

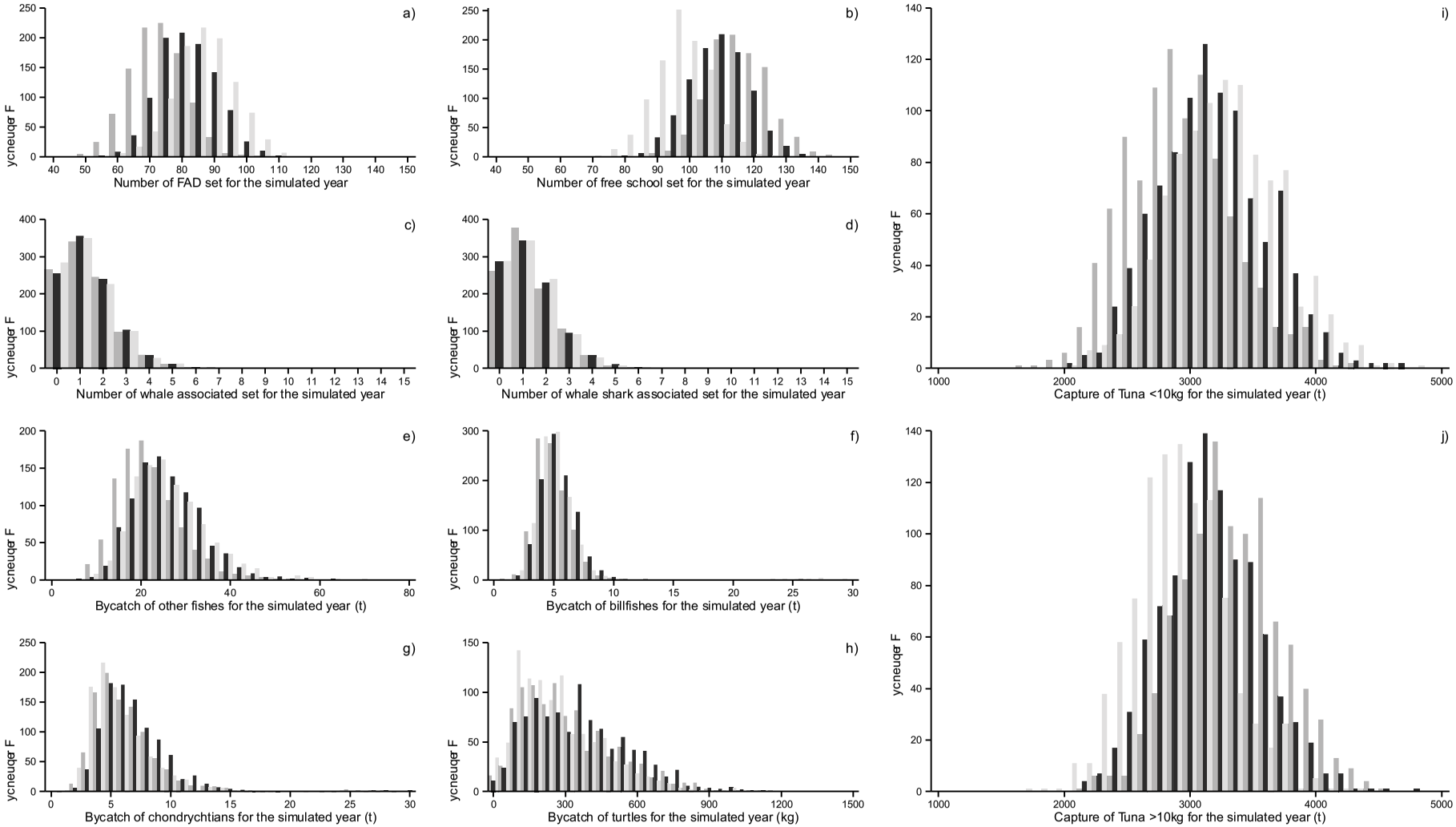
Appendix 6.B

Summary of the logbook and scientific onboard observer data, over the 2005–2014 period, used to compile the probabilities used for the Monte Carlo simulations.

		Atlantic Ocean		Indian Ocean	
		French	**Spanish**	**French**	**Spanish**
Logbooks	Total number of vessels	20	53	36	36
	Mean nb. of vessel per year	11 ±0.4	30 ±1.0	17 ±0.9	25 ±1.9
	Total nb. of fishing sets	19 210	37 675	36 028	59 958
	FAD (% total nb. of sets)	28.1	46.4	52.1	65.3
	FSC (% total nb. of sets)	68.4	51.9	44.3	33.6
	WHA (% total nb. of sets)	2.4	0.7	2.7	0.3
	WHS (% total nb. of sets)	0.9	0.7	0.4	0.4
	Total tuna catch (t)	330 658	847	776 78	1 693 233
	Catch <10kg (% total catch)	41.5	66.4	56.5	75.6
	Catch >10kg (% total catch)	55.5	30.0	41.8	22.5
Observer	Total nb. of fishing sets	10466		5137	
	FAD (% total nb. of sets)	32.5		50.4	
	FSC (% total nb. of sets)	65.0		47.0	
	WHA (% total nb. of sets)	1.8		1.8	
	WHS (% total nb. of sets)	0.7		0.4	
	Total bycatch chondrichthyans (t)	268		238	
	Total bycatch other fishes (t)	883		1599	
	Total bycatch billfishes (t)	140		159	
	Total bycatch turtles (kg)	14 753		2120	

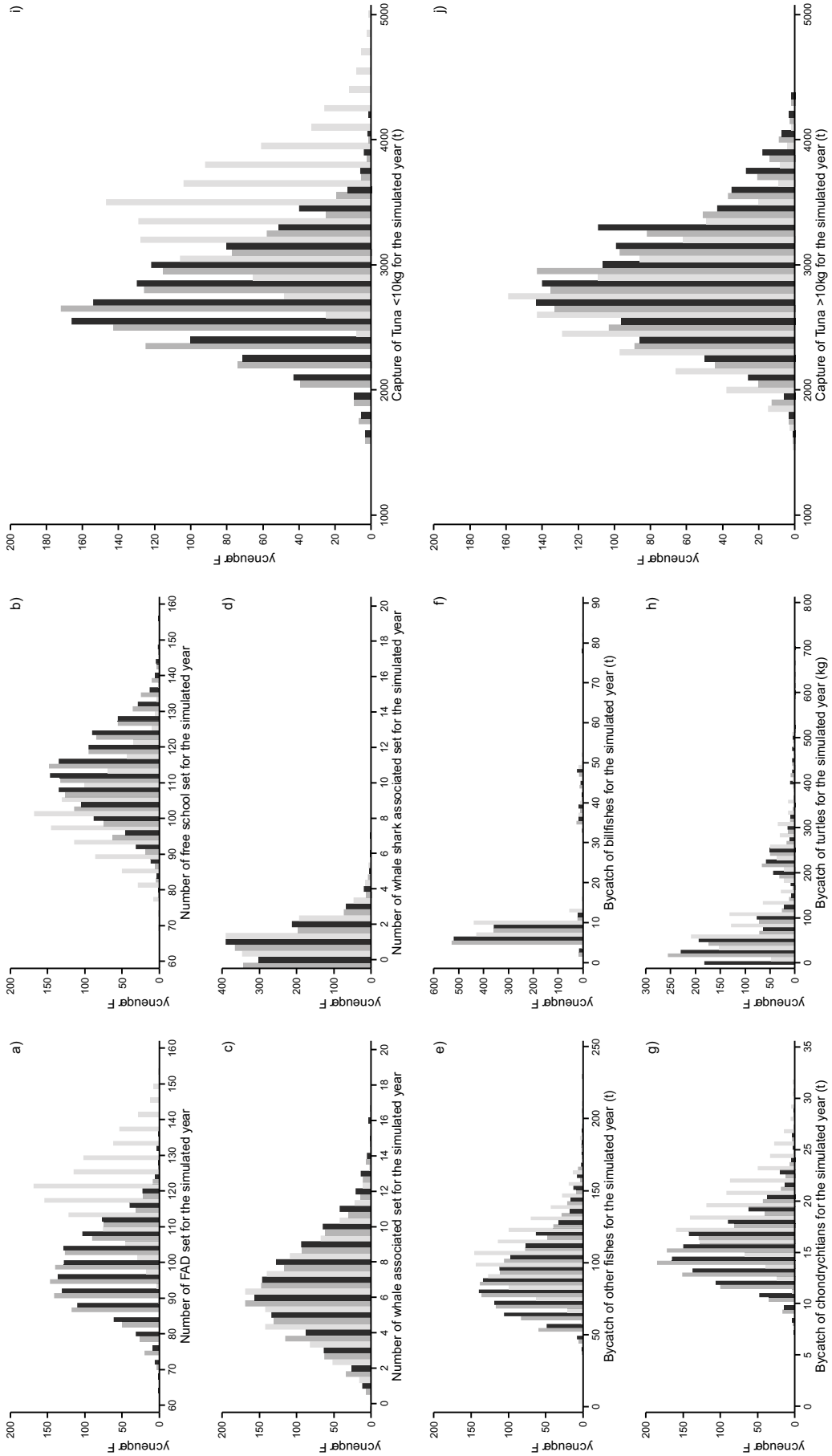
Appendix 6.C

Simulated fishery indices: a) FAD set, b) free school set, c) whale associated set, d) whale shark associated set, e) bycatch of other bony fishes, f) bycatch of billfishes, g) bycatch of sharks, h) bycatch of turtles, i) catch of tuna < 10 kg and j) catch of tuna ≥ 10 kg, for one Spanish purse-seiner over one fishing year with a moratorium on FAD during season 1 and 4 (dark grey = scenario 1; black = scenario 2) in the Atlantic Ocean, compared to the baseline (light grey).



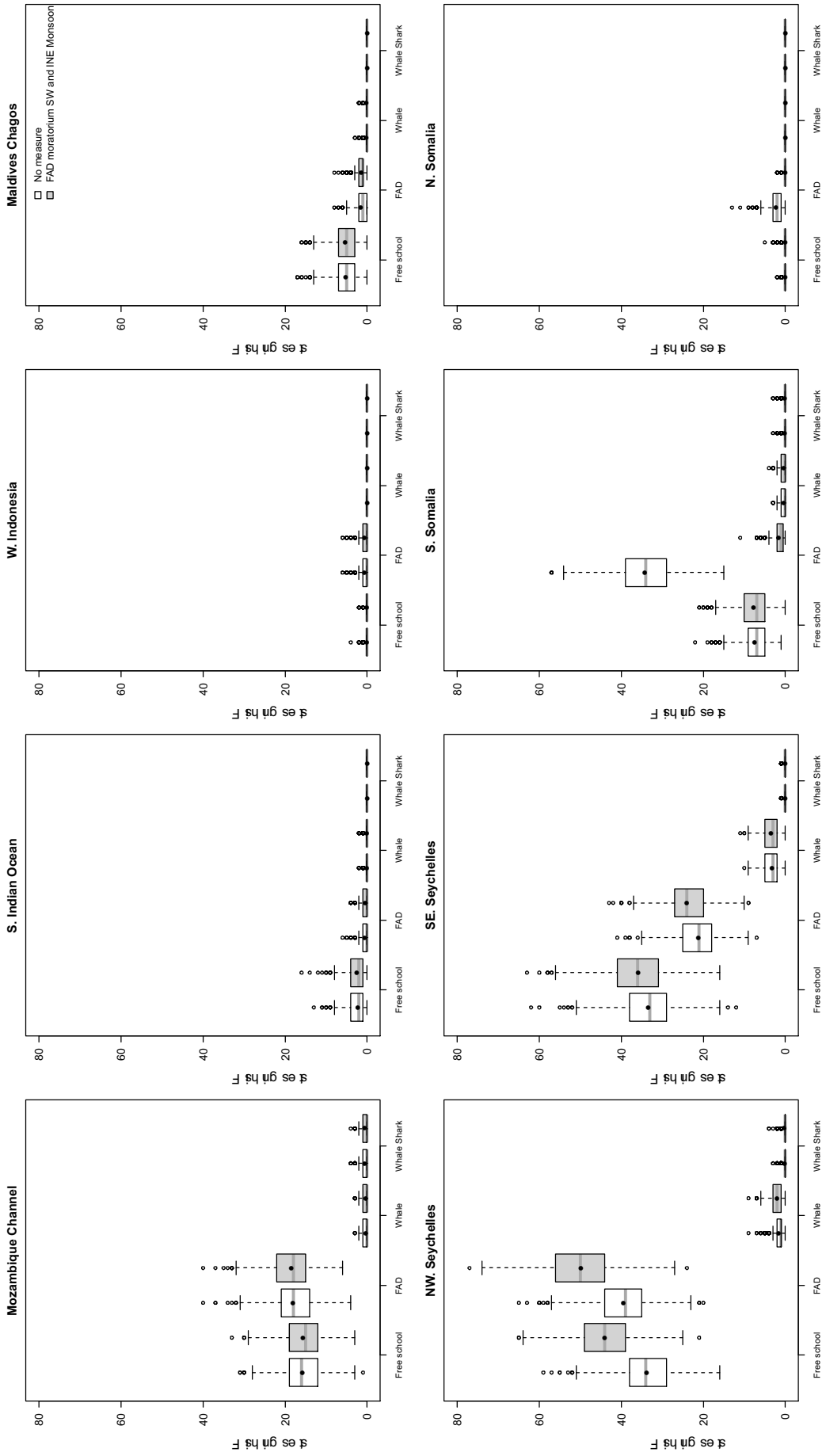
Appendix 6.D

Simulated fishery indices: a) FAD set, b) free school set, c) whale associated set, d) whale shark associated set, e) bycatch of other bony fishes, f) bycatch of billfishes, g) bycatch of sharks, h) bycatch of turtles, i) catch of tuna < 10 kg and j) catch of tuna ≥ 10 kg, for one French purse-seiner over one fishing year with a moratorium on FAD during SW and INE monsoon periods (dark grey = scenario 1; black = scenario 2) in the Indian Ocean, compared to the baseline (light grey).



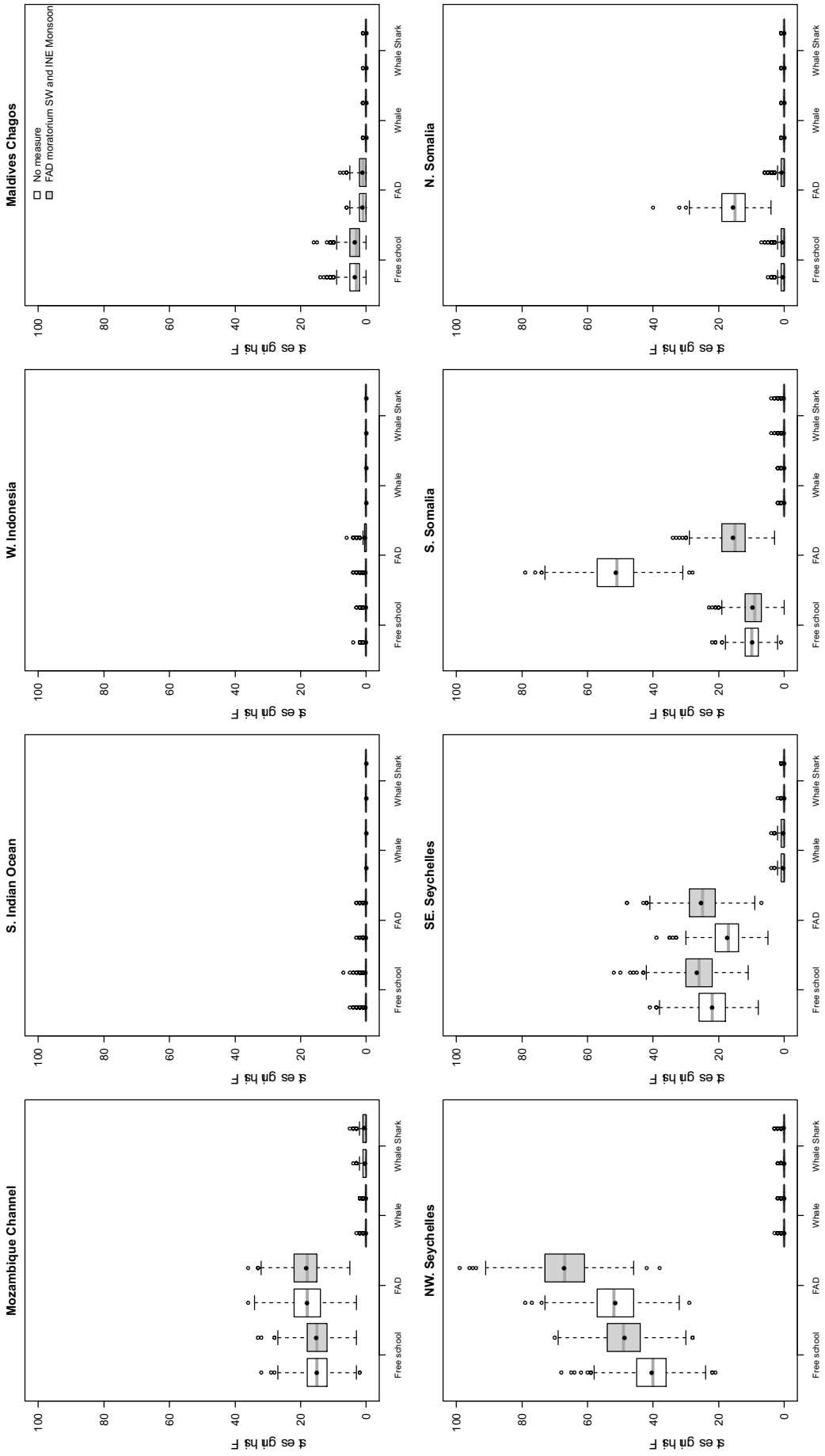
Appendix 6.E

Number of sets per fishing mode for the simulation of one French purse-seiner over one fishing year in the Indian Ocean, for the baseline scenario (white) and for the scenario 1 of a moratorium on FAD during SW and INE monsoon periods (grey).



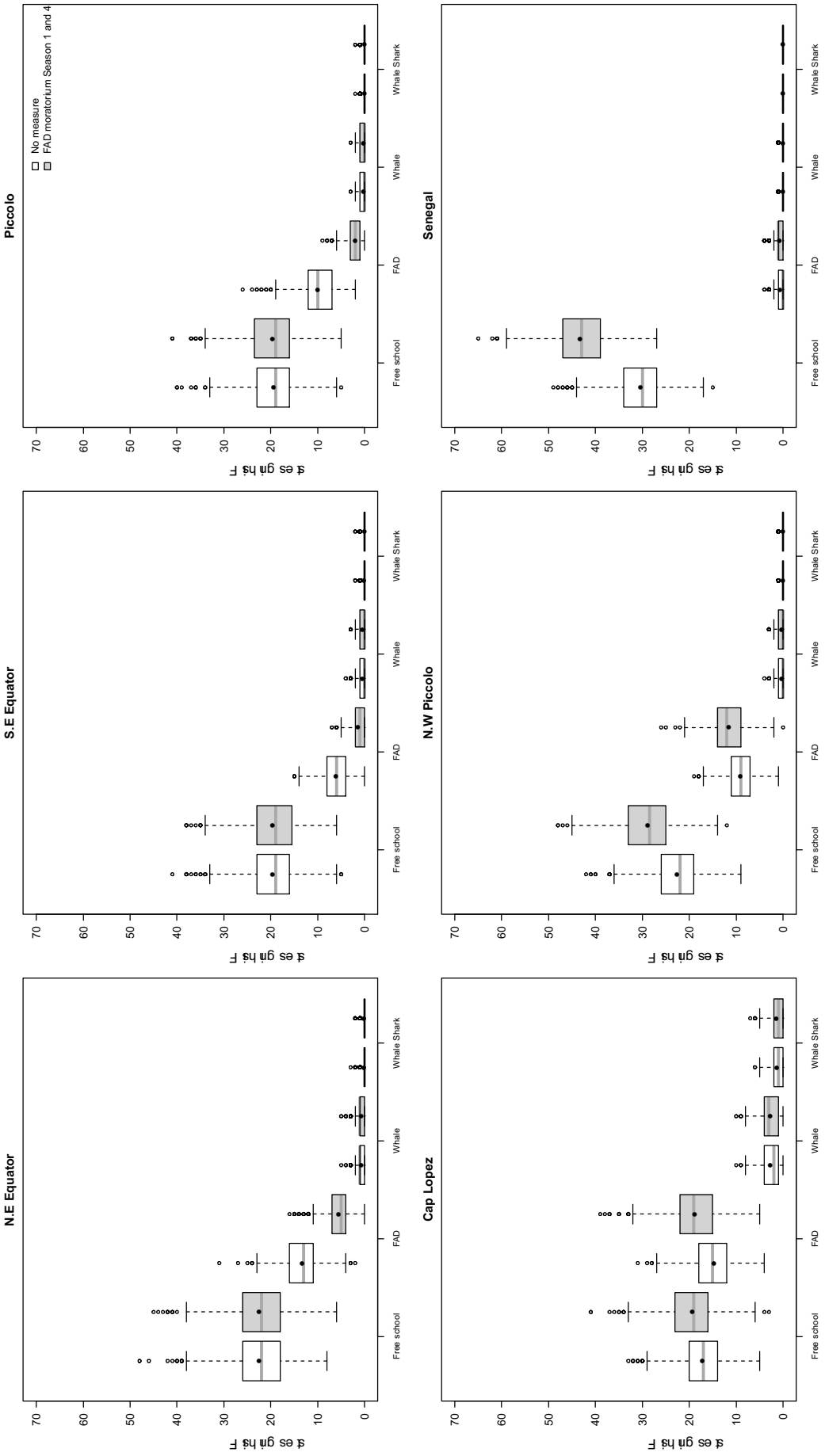
Appendix 6.F

Number of sets per fishing mode for the simulation of one Spanish purse-seiner over one fishing year in the Indian Ocean, for the baseline scenario (white) and for the scenario 1 of a moratorium on FAD during SW and INE monsoon periods (grey).



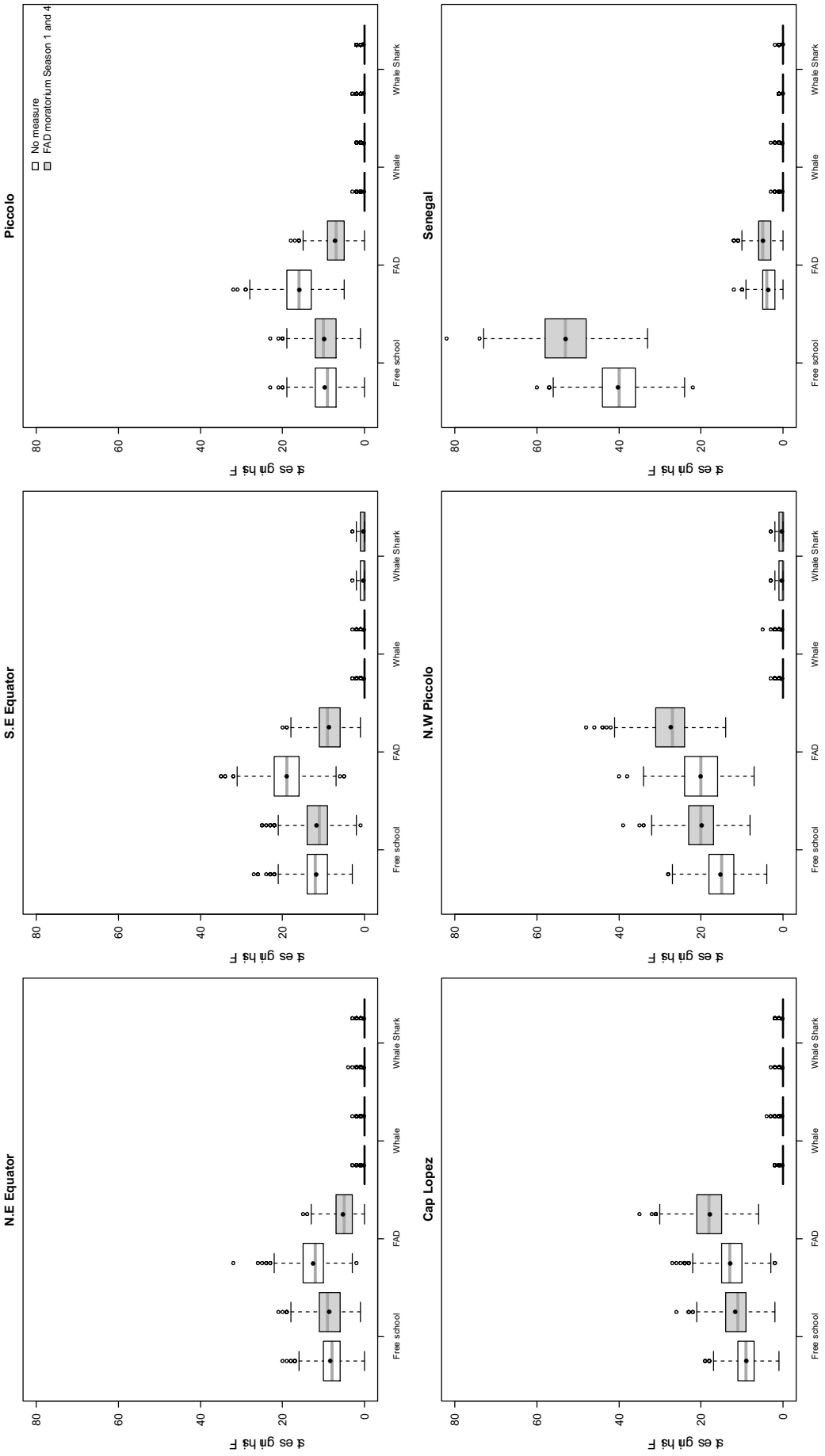
Appendix 6.G

Number of sets per fishing mode for the simulation of one French purse-seiner over one fishing year in the Atlantic Ocean, for the baseline scenario (white) and for the scenario 1 of a moratorium on FAD during seasons 1 and 4 (grey).



Appendix 6.H

Number of sets per fishing mode for the simulation of one Spanish purse-seiner over one fishing year in the Atlantic Ocean, for the baseline scenario (white) and for the scenario 1 of a moratorium on FAD during seasons 1 and 4 (grey).



Chapter 7

General discussion

7.1 Megafauna species in the tropical tuna purse-seine fishery, toward an Ecosystem Approach to Fishery management

7.1.1 Whale sharks, cetaceans and tuna purse-seine fishery

Worldwide, many marine megafauna species are declining as indicated by records of targeted or incidental catch (biomass) for most shark and ray species, and abundance Wallace *et al.* 2013 Magera *et al.* 2013 Dulvy *et al.* 2014). The main threat to marine megafauna populations has been identified as the Lewison *et al.* 2004). While occurring in all tropical oceans worldwide, the tropical tuna purse-seine fishery has generally lower bycatch rates, including megafauna species, than other fisheries such Kelleher 2005). However, the purse-seine fishery could still further impact some populations already declining or could also potentially directly impact some populations of vulnerable species. For instance, this was the case in the eastern Pacific Ocean, where high dolphin mortality rates induced by the purse-seine fishery have impacted several populations in the 1960s and 1970s (see Chapter 1). In the tropical eastern Atlantic (EAO) and western Indian Oceans (WIO), even if the same species of tunas and dolphins can be found, no such interaction with dolphins has been considered to occur. The main fishing modes in the two last oceans are FAD and free school sets. However while some sets have been known to be made on tuna schools associated with baleen whales and whale sharks, little information on this topic existed in the literature prior to this thesis. As a consequence this thesis aimed to fill this gap through the investigation of the spatio-temporal co-occurrence and potential interactions of whale sharks, cetaceans and the tuna purse-seine fishery within a conservation perspective. The different objectives of the thesis were therefore the following: i) to define the spatio-temporal co-occurrence and interactions existing between whale sharks, several cetaceans species and the tuna purse-seine fishery in the EAO and WIO (Chapter 2 and 3), ii) to assess the potential impacts of the fishery on these megafauna species (Chapter 2 and 3), iii) to identify environmental variables linked to the co-occurrence between whale sharks, cetaceans and the purse-seine fishery (Chapter 4), iv) to characterize the species composition and size spectrum of targeted tuna, as well as bycatch diversity in the sets associated with whale sharks and baleen whales (Chapter 5), and v) to investigate potential side effects of megafauna conservation measures and fishing effort regulation measures on the targeted catch, the bycatch and the number of megafauna associated fishing sets (Chapter 6).

After a general introduction presenting the tuna purse-seine fishery, the study areas

as well as a review of the knowledge available in the literature concerning megafauna species associating with the purse-seine fishery (Chapter 1), this thesis investigated throughout five chapters the different scientific issues mentioned above. Overall in the EAO and WIO, whale sharks and baleen whales are directly interacting with the purse-seine fishery, in the sense that both are mostly registered during a fishing set (Chapters 2 and 3). On the contrary, delphinids, although they are present in fishing areas and widely distributed among areas and seasons, they only co-occur with the fishery. In these oceans, very few dolphin sets have been documented (Chapter 3). Similarly, sperm whales sightings were generally little registered in observer and logbook records. Whale shark associated sets are mostly incidental (i.e. in 80% of the sets individuals were not seeing prior the setting of the net), but also sometimes intentional (20%) (Chapter 2). On the other hand, baleen whales can be easily detected from a distance when breathing at the surface, and sets are voluntary made in the vicinity or around baleen whales (Chapter 3). Purse-seiners have been found to directly interact, possibly intentionally, with two megafauna groups: baleen whales and whale sharks. After drawing this conclusion, the rest of the manuscript has been mainly focused on baleen whales and whale sharks.

Both of these co-occurrences and interactions with the tuna purse-seine fishery have been localized in specific areas and periods. In the EAO, whale shark and baleen whale associated sets mostly occur in the coastal area from Gabon to Angola from April to September (Chapter 2 and 3). In the WIO, both fishing modes were mostly found in the Mozambique Channel from April to May, and baleen whale associated sets were also high in an area east of Seychelles from December to March (Chapter 2 and 3). These hotspots of higher co-occurences have been identified as highly productive environments (river discharge, high eddy activity and upwelling). As such, it was not surprising that the co-occurrence of whale sharks and baleen whales with the purse-seine fishery have been found to be the mostly linked to Chlorophyll-a concentration, as well as other proxy of productivity, such as distance to the continental shelf or eddy kinetics energy (Chapter 4). Both whale sharks and baleen whales (*Balaenopteridae*) are filter filters, and the latter due to its feeding behavior (lunge feeding) have to feed in patch of high prey density to be energetically efficient. Therefore, it is not surprising that outside Antarctic feeding grounds baleen whales will be encountered in highly productive tropical areas. Hence, feeding in association (for cetaceans) or in similar areas, may therefore be considered as the main reasons for the co-occurrence between both megafauna groups and tuna schools. However, in spite of the association between baleen whales and tunas been presumably mainly to feed on shared prey species, some whale species may be present in fishing areas primarily for mating and calving. This is for instance the case in the coastal area from Gabon to Angola, as well as

the Mozambique Channel, where the main period of co-occurrence between baleen whales and the purse-seine fishery corresponds to winter presence in tropical mating and calving grounds. However, in the east of Seychelles area, the period presenting baleen whales and fishery co-occurrence (November–March) does not match tropical winter presence of baleen whales, as well as historical peak in whaling catches in Seychelles (mostly humpback Robineau 1982 Robineau 1982) hypothesized that sightings (and whale associated sets) in the east of Seychelles area were mostly Bryde's whale present year-round in tropical waters. On the other hand, for whale shark, the lack of data on its biology and ecology, especially as adults, precludes any other assumption than feeding behavior. In addition, in the WIO, megafauna fishery co-occurrence was also linked to monsoon seasonality (Chapter 4). Indeed, in this ocean the co-occurrence reflected 1.7 1.8) while in the EAO it was dominant during one specific season and area. Nonetheless, considering the high fishing effort along the Somalia EEZ during the period of the upwelling (June–September) and knowing the link between megafauna/ fishery co-occurrence and high productivity, one could have expected that more whale shark and baleen whale sets and sightings would be recorded during the Somalia upwelling. The fact that few sightings have been recorded in this area may be explained by i) the high FAD fishing in this period and area, which may limit the search for other tuna schools (i.e. associated with whales and whale sharks), ii) the spatial extent of the upwelling, especially north of the fishing areas and close to shore (piracy area), leading to the absence of spatial co-occurrence between fishery and megafauna species, or/and iii) the low populations size in this northern hemisphere area.

One of the main conclusion of this thesis is the limited apparent impact caused by the tuna purse-seine activities on both whale sharks and cetaceans. Firstly, about the latter, the mortality of 3 humpback whales and 8 pantropical spotted dolphins have been recorded in the EAO (1995–2011). This therefore represents cetaceans' immediate apparent survival rates of 92% and 100%, in the EAO and WIO, respectively (Chapter 3). These high apparent survival rates may be explained by the fact that whales either dive during 7.1). It should be mentioned that there might be some behavior difference among species. Due the difficulty of identifying species at sea, observers do not often record the species involve in the interactions. Nevertheless humpback whale may be relatively easily distinguished from sei, fin and Bryde's whales. Hence, it appears that most sets involved these three species (based on observers records, pictures and field work at sea), while sets on humpback whales are more scarce. This assumption, based on field observations, agrees with the humpback whale's ecology, as mating and calving areas are very close to shore. However this is the

only species that have, to our knowledge, stayed inside the net until the sack (pictures and 7.1.d), and that had to be release using the same method over the float line as for whale sharks or being towed out by the skiff. In addition, the only baleen whale's mortality records in European purse-seine observer data were of humpback whale. The impact of the purse-seine fishery may therefore vary depending on the whale's species, as well as individuals' maturity stage. Indeed Romanov (2002) has recorded the mortality of a young sei whale after encirclements in purse-seine nets in the WIO. In general we found a limited impact of the fishery on cetaceans. However, post-encirclement survival (i.e. humpack whale) and the non-lethal impacts of encirclement have not been assessed.

Secondly, about whale sharks, two individuals have been recorded dead (i.e. one in each ocean), representing an immediate apparent survival rate of 99%. However, contrary to baleen whales, rarely encircled or escaping by themselves, whale sharks are most of the time encircled and have to be released by the crew from the sack. In the past, whale sharks have been towed up by the tail and lifted onboard (individuals <6–7m), or towed out of the net at the surface by the skiff (observers records and pictures). Nowadays a safe release method has been described and is already used by some purse-seine crews (Chapter 2). In order to assess the longer term post-encirclement survival, a satellite tagging experiment has started in 2014. That year, six whale sharks were tagged and release with the "safe release" method. Encouraging results were found, as all survived (one did not report) at least 21 days after encirclement. We are currently waiting for the results from this year tagging, as five whale sharks have already been tagged in June 2016 in the EAO, with one individual released using the skiff towing out the animal by the tail after failure of releasing the whale shark using the "safe release" method. Further tagging will thus allow assessments of post-encirclement survival when release from encircling purse-seine nets, as well as movements outside fishing areas.

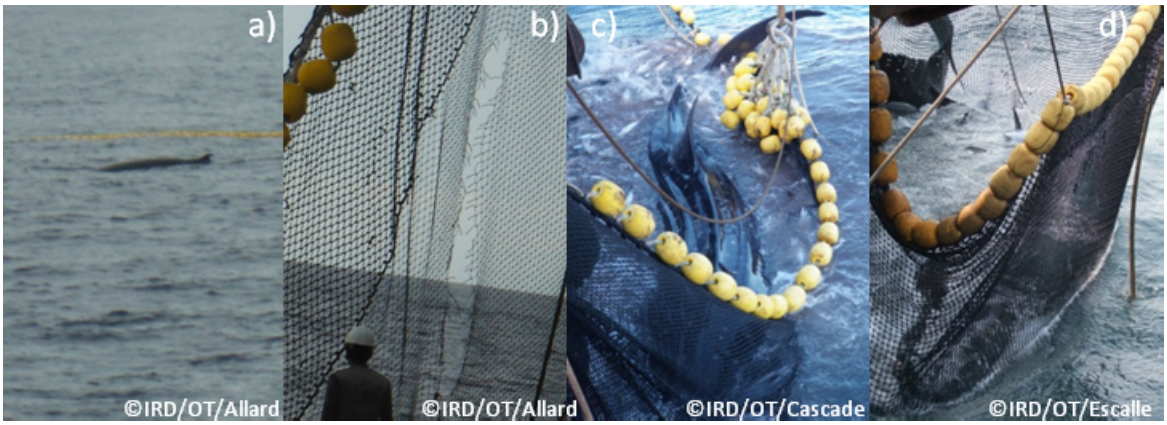


Figure 7.1 a) Encircled baleen whale (sei, fin or Bryde's whale) and b) hole left in the purse-seine net when escaping, c) whale shark and d) humpback whale encircled in the sack.

The investigation of the tuna species and size category compositions captured in whale and whale shark associated sets showed that whale associated sets did not differed from free school sets in term of species and size of targeted tuna species as well as bycatch. Whale shark sets, however, were intermediate between free school and FAD sets, although closer to the second one in terms of tuna catch and bycatch occurrence but differed in terms of tonnage and diversity in the bycatch (Chapter 5). Whale associated sets present higher risks of failure, with the tuna school escaping with the baleen whale. However, when successful, it leads to the highest average catch per sets among all fishing modes, with mostly large yellowfin tunas. On the contrary, whale shark associated sets are mostly successful but catches the least tuna catch per set. The catch is then composed either of i) a mix of skipjack, yellowfin and bigeye (both mostly >10kg), ii) only skipjack, or iii) only large yellowfin (mostly >30kg). Half whale sets and more than 80% whale shark sets presented bycatch (Chapter 5). For both of these fishing modes, bycatch beta diversity showed similarity with free school sets, while FAD sets highly differed from these three fishing modes. Silky shark was the most abundant bycatch species in both whale and whale shark associated sets, with mostly large individuals. Other bycatch species included chondrichthyans (blue shark, manta rays), billfishes (mainly sailfishes in whale associated sets and marlins in whale shark sets), porcupinefishes, pufferfishes and pilot fishes. It should be noted that finfish species commonly recorded on FAD sets were absent from whale shark associated sets. This therefore reinforces the intermediate status of whale shark sets in terms of tuna and bycatch species composition. Species associated with whale, including tunas, include species that may swim similar speed (chondrichthyans and billfishes). For whale sharks, although it swims slowly, the fact that it is moving faster than drifting FADs and sometimes diving, may limit its aggregating behavior. This may explain why several species commonly encountered under FAD will not aggregate under whale sharks, likely due to its "unstable" state (i.e. swimming behavior) in time.

Main areas of whale sharks and cetaceans co-occurrence and interactions with the purse-seine fishery do not match period and area of high FAD fishing (Chapters 2, 3 and 6). For this reason it is unlikely that spatio-temporal fishing effort regulations to limit FAD fishing (no-take zone, FAD moratorium) will highly affect megafauna fishery interactions. This was confirmed by past time-area regulations on FAD, showing no effect on megafauna associated fishing sets (Chapter 6). The only exception being that limited fishing activities in the Somalia EEZ (and then 300 nm around it) led to slight decrease in the number of whale shark associated sets (already low). Similarly the consequences of simulated large (six-month over wide areas) FAD moratoria in the EAO were limited on whale and whale shark associated fishing sets. However, in the WIO, a slight increase in whale and whale

shark associated sets was detected around Seychelles in case of a simulated six-month moratorium in the Somalia area. While the period of the moratorium (June–November) preceded the main period for whale associated sets (December–March), some of these sets were already performed in this area during the INE monsoon period (October–November) 3.2). Hence, if we consider that most baleen whales present in the east of Seychelles area during spring and summer months are resident Bryde's whale, the fact that more sets are performed during NE monsoon compared to the rest of the year only derive from the higher fishing effort during this period. Therefore increasing fishing effort in the region during INE monsoon (but also ISW and SW monsoon when other whale species are present) will most probably lead to increasing whale associated sets. Conversely, megafauna conservation measures (whale or/and whale shark associated sets ban) also showed limited consequences on fishing effort distribution and strategies, tuna catch and bycatch. This is mainly due to the limited number of whale and whale associated sets nowadays (Chapter 6). Slight increase of FAD and free school sets were nevertheless detected in the simulations' results when i) both fishing modes were banned, ii) the ban applied to the whole ocean, iii) the ban applied to the two seasons with higher whale associated sets. In these cases, the tuna catch was not affected, showing limited consequences of these bans for fishers. Slight decrease of billfishes and chondrichthyans was detected. While the occurrence may by lower than on FAD sets, these are the two bycatch groups the most encountered in whale and whale shark associated sets (with higher number of individuals per sets for silky sharks in the EAO). These two groups may therefore also be expected to increase in case of fishing effort relocation on megafauna associated sets.

To sum up, most megafauna associated sets in the EAO and WIO involve whale sharks or baleen whales. Both sets are mostly concentrated during specific seasons and areas, which are mostly linked to highly productive environments. In terms of tuna catch, whale associated sets are very close to free school sets (i.e. large yellowfin) but catches larger tuna schools. The bycatch is similar as well (sharks, manta rays, sailfishes, sometimes finfishes), except that the most abundant taxa is the silky shark. Whale sharks sets are closer to FAD sets in terms of tuna catch (mostly skipjack but also the presence of small yellowfin and bigeye tunas), as well as the fact that bycatch occurs in most sets. However they are somewhat intermediate with free school sets as large yellowfin tunas (>10 kg) are captured in both mono and multispecific sets, and the tonnage and diversity of bycatch are closer to whale and free school sets. Finally, the main seasons and periods of FAD sets and megafauna associated sets differed and the latter are still relatively low nowadays. Therefore time-area fishing effort regulations on FAD or megafauna conservation measures are unlikely to highly affect one another.

7.1.2 Possible candidate areas for conservation planning

As mentioned previously, for both megafauna group studied, the main environmental variables linked to their co-occurrence with the purse-seine fishery is ocean productivity. Therefore, it suggests that whale sharks and cetaceans feed in association or in co-occurrence with tuna schools within these fishing areas. However species may also be present in fishing areas for other reasons such as reproduction or migration between feeding or reproductive areas. For instance, for baleen whales most fishery/whale interactions occur within the range

Robineau 1982 Weir 2007). This is however not the case for the east of Seychelles area, which most likely mostly involve Bydre's whale during the Antarctic feeding period of the other whales' species, and therefore may also be feeding in the area.

Firstly, regarding baleen whales, it has been considered that some species are feeding in the tropical waters of the purse-seine fishing areas (e.g. Bryde's and sei whales), while others will only feed in summer Antarctic feeding grounds (fin, blue and humpback whales) (Chapters 1, 3 and 4). The first category includes Bryde's whale potentially present Best 2001) but also sei whale, which has been observed Budker and Collignon 1952). On the other hand, the second category (i.e. non-feeding) includes humpback, fin and blue whales, which were Budker and Collignon 1952). This has however now been contradicted by several studies. For all these species, feeding has Owen *et al.* in press) or Silva *et al.* 2013), or directly within the breeding areas Geijer *et al.* in press). This therefore better explains why other species than Bryde's and sei whales (especially humpback whale easily distinguished from the others) have been identified in whale associated sets (i.e. in feeding association with tuna schools).

Despite the relative low apparent mortality rates of the purse-seine fishery on baleen whales, populations' sensitivity should also be mentioned through populations' size and abundance trends, to correctly investigate potential impact on the species involved. Such estimates do not exist for all populations or are based on historical whaling catch records only. It is however not the case for humpback whale, which is one of the most studied baleen whale found in tropical waters, presumably due to its presence in very shallow area (mating and calving) and its spectacular breaching and slapping behaviors at the surface. Hence, populations' sizes are relatively well known worldwide. Both the southwest Africa (i.e. Angola to Togo) and the southeast Africa (WIO below the equator) humpback whale populations have been Bettridge *et al.* 2015). Abundance trend are

unknown (southwest Africa) or considered increasing (southeast Africa), but both populations Bettridge *et al.* 2015). For the other species, abundances are less precise. During the whaling period, southern hemisphere populations were divided into six statistical areas, with the area III covering both the southwest and southeast African populations. For fin whale, there is no currently accepted population estimates or abundance NOAA 2011). The latest southern hemisphere population estimate (1979) was of Gerber *et al.* 2000) based on historical catch records, but low confidence was given to this estimation due to presumed catch over-reporting to hide illegal catches of other species. Keeping in mind the presumed overestimation, and considering all stocks equally, this would lead to ∼14 000 individuals in area III. Similarly, for Bryde's whale there is also no currently accepted IWC southern hemisphere population estimate. Historical (non conform survey design and analysis) population estimates of the statistical area III was IWC 1981). In the Atlantic Ocean, the Bryde's whale inshore stock was nevertheless estimated at 582 (± Best *et al.* 1984). Finally, sei whale Mizroch *et al.* 1984). Therefore, again when considering a simplified vision of the reality where both populations would have the same size, abundance of southwest and southeast African populations could be considered of <7000 fin whale, 2600 Bryde's whale and <600 sei whale each. Nowadays the number of European purse-seine sets on baleen whales is of 20–200 per year and per ocean (up to 650 in the 1980s and 1990s; logbook data), with an apparent mortality rate of 3% (EAO and WIO combined, Chapter 3). Thus, the impact of the purse-seine fishery on baleen whales' populations could be considered relatively low, especially in perspectives of the high yearly catches during the whaling era (e.g. up to 1500 humpback whale taken per year in Gabon (1920–1950) and up to 2500 per year (1950–1960) in the Antarctic, as well as up to 7000 sei Budker and Collignon 1952 IWC 1960 1970). Yet, it could slow down populations' recovery, especially when added to other threats and stress suffered by populations and considering that co-occurrence occurs in calving and breeding areas where juveniles, more sensitive to encirclements, could be involved. Furthermore, apart from the southern hemisphere, baleen whales/purse-seine fishery co-occurrence has also been recorded in the coast from Mauritania to Guinea in the EAO and above the equator in the WIO. While the number of whale associated sets and encirclements are lower than in the main areas of co-occurrence, whales' populations also appear very low in these areas. Indeed, humpback whale (as well as sei whale and possibly other species) from the northern hemisphere have winter (January–May) mating and calving grounds in Cape Verde (known historical whaling area) and north-west African waters Hazevoet and Wenzel 2000 Bamy *et al.* 2010 Hazevoet *et al.* 2011). Similarly, in the

northern part of the WIO (i.e. Arabian Sea) populations of non-migrating humpback and blue whales, as well as records of some other species (sei, fin and/or Bryde's whales) have been Robineau 1982 Mikhalev 1997 Clapham and Ivashchenko 2009 Anderson *et al.* 2012 Bettridge *et al.* 2015). In both of these areas, humpback whale population is estimated at less than 100 individuals and has therefore been classified as high risk of Bettridge *et al.* 2015). The little information on the other baleen whale species present in these areas preclude any population estimates, but may also be an indication of low population abundance. Nevertheless, when considering the humpback whale only (low population size, as well as the fact that it is the species with mortality events recorded in the European purse-seine fishery), even few mortality induced by the purse-seine fishery may not be negligible to these small northern hemisphere populations. In addition, given the localization and timing of the presence of these populations (within or at the boundary of the highest FAD areas, which periods corresponds to the Somalia and Mauritania upwellings) we may expect, in case of FAD fishing regulation measures, some effort relocation on whale sets. This may be particularly important in the WIO, if fishing grounds extend to the north, and may therefore potentially limit populations' recovery. Overall, it has been highlighted that within main areas of co-occurrence, baleen whales populations appear to have abundances likely to support the apparent mortality rates recorded by the European purse-seine fishery, especially in view of historical whaling catch records. However, in addition to mortalities induced by the purse-seine fishery, populations are also subject to other impacts and stress which, when cumulated, may reduce populations' recovery. In addition, northern hemisphere populations appear to have very low abundances, especially for humpback whale. Thus even few mortality events induced by the fishery may impact these populations.

Secondly, regarding whale shark, as filter feeder present year-round in tropical waters, it makes sense to assume that its co-occurrence with the purse-seine fishery is mainly linked to high productivity. However some other features linked to reproduction may play an important role in conservation. For this species, reproduction is still poorly known and therefore any new information is relevant. In both oceans whale sharks recorded by the purse-seine fishery are mostly large individuals (>8–9 m, i.e. adult females). In the EAO, the main area of co-occurrence and interactions is the coastal area from Gabon to Angola from April to September (Chapter 2). A recent study have found that whale sharks 7.2) Clingham *et al.* 2016a). Feeding, as well as the first observation of mating behavior, have been observed. In addition, preliminary results from satellite tagging Clingham *et al.* 2016b). Therefore we may hypothesize that, at least mature females, might aggregate in St. Helena

to mate from January to March then migrate to the coastal area of Gabon and Angola to feed from June to September (Chapter 4). No clear return movement toward St. Helena could be identified in our limited tagging data. Yet interestingly, some individuals showed westward movement, with one individual traveling 1500 km in a relatively straight line for 21 days (Chapter 2 and Appendix 2.B). We may therefore hypothesize on several reasons (e.g. reproduction, calve, other feeding area) for such migration. One assumption has been raised by Hueter et al. (2013) to explain a fast and straight forward migration of a female from 7.2). These authors proposed that mature females might migrate to oceanic waters to calve. Indeed, in spite of the few Rowat and Brooks 2012), 7.2) have already been identified in Wolfson 1983 Kukuyev 1996). Moreover, from observer programs, five additional neonate or small juveniles have being reported as encircled by tuna purse-seiners in 1995 (two individuals of ∼ 7.2 7.3). In view of the presence of neonate individuals in the equatorial Atlantic area, it can be assumed that the large individual recorded in this thesis as heading straight toward this 7.2) may also be migrating to calve in the open sea. While the precise dates of capture of the neonates (50–60 cm) was usually unknown, when recorded it was in November or March, which corresponds to the presumed equatorial mid-Atlantic presence of Hueter *et al.* 2013) also suggested possible mating behavior in Ascension Island or Saint Peter and Saint Paul Archipelago, where large (8–14 m) whale Hazin *et al.* 2008 Hueter *et al.* 2013). It is not evidenced yet whether small whale sharks will be capable of self movement, but in any case it is unlikely that they would travel long distances. Therefore, the small whale shark (69 cm) encircled in Mauritania in July must have been born in the area. In the Azores, large whale sharks Afonso *et al.* 2014). Given the size of the other neonate whale sharks, this individual may be few months old (based on aquarium Rowat and Brooks 2012), indicating that it was born in spring. This could therefore correspond to the presence of sharks from either the Gabon or the Azores areas. Finally the identification of oceanic calving areas may be of importance for conservation of the species. The duration of the gestation is unknown for whale sharks, but could be less than one year (5–12 months for smaller ovoviviparous shark of the same Castro 2000 Huveneers *et al.* 2007) or up to three years (similarly Hoelzel *et al.* 2006). While less individuals are encircled in equatorial mid-Atlantic and Mauritania areas than in the Gabon hotspot, the Rowat and

Brooks 2012), as well as small juveniles, more sensitive to encirclements, make these region as potential key conservation areas.

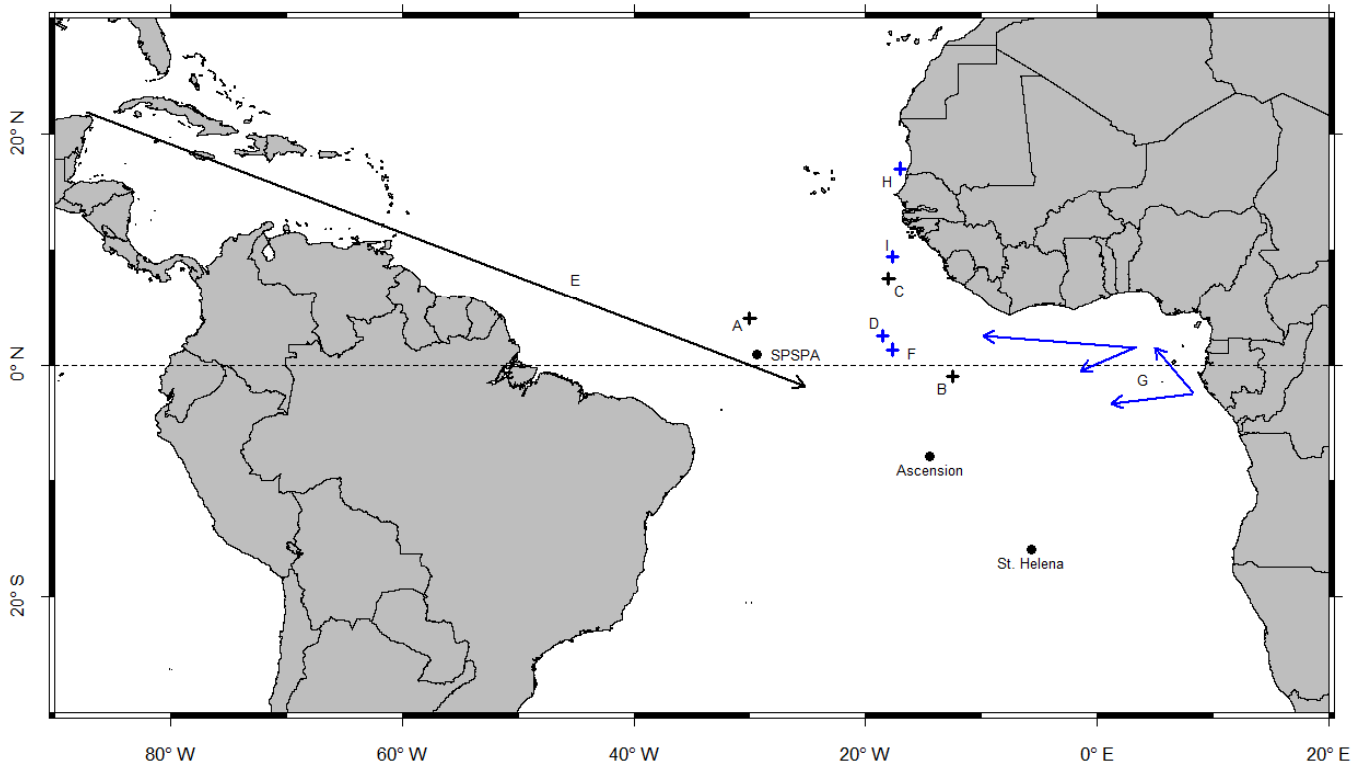


Figure 7.2 Large whale sharks tracked migration, neonate observations and remote Island where adults and small juveniles have been recorded (St. Helena, Ascension Island and Saint Peter and Saint Paul Archipelago SPSPA) in the tropical Atlantic Ocean. A. one female of 56 cm caught in a Kukuyev 1996), B. one male of 57 cm caught by purse-seiner in march 1980

Wolfson 1983 Kukuyev 1996), D. two individuals ∼ 7.3.a) caught by French purse-seiner, in November or December 1996 (most likely period and position from logbook data), E. track of a 7 m female from Hueter *et al.* 2013), F. one individual of 120 cm caught by French purse-seiner in December 2012 (observer data), G. four females tracked from June/July to August 2014 (21–71 days, see Chapter 2), H. one individual of 69 cm caught and release alive by 7.3.b), I. one female of 185cm caught and 7.3.c).

In the WIO, less whale shark encirclements have been recorded, but also mostly involved large individuals. In addition, in the literature most sightings from this ocean are from coastal juvenile (3–7 m) aggregations, where larger individuals (8–10 m) were also sometimes Riley *et al.* 2010 Rowat *et al.* 2011 Rohner *et al.* 2015). Apart from the north of the Indian Ocean (India and Pakistan) where very few purse-seine fishing occur, the only neonate whale shark recorded from this Colman 1997). Therefore it was not possible

to identify similar possible key areas in this ocean. Tracked whale sharks in this ocean included one female (6–7 m) tagged in south Mozambique (February) that traveled to the Brunnschweiler *et al.* 2009), as well as immature individuals tagged in Seychelles (October–November) that moved to three different direction Rowat and Gore 2007).

Figure 7.3 a) Neonate (∼50cm), b) and c) small juvenile (120 and 185 cm) whale sharks captured by tuna purse-seiner in the eastern Atlantic Ocean in 1995, 2014 and 2015.

Finally, population abundance is unknown for whale shark, as mature individual Castro *et al.* 2007) estimated, based on genetic studies, a global female effective population size of 119 000–238 000 individuals. This is therefore rather high compared to the worldwide known whale shark sightings. A large proportion of individuals, especially mature ones, may therefore inhabit oceanic waters where they may remain undetected. In the European purse-seine fishery, the number of yearly whale shark associated sets is of 20–250 individuals in the EAO over the last 15 years (up to 550 in the 1980s and 1990s) and of 0–150 in the WIO since 1980 (logbook data). In spite of the absence of population abundance for the EAO and WIO, one indicator of population sensitivity to fishery is the annual catches of whale shark was of 450–700 individuals in the Philippines, 250 in Tawaïn and 430 in India, which has lead to population decline in the 1990s (see Chapter 1). Therefore annual whale shark encirclements may not be negligible if mortality rates are higher than the apparent ones estimated in this thesis (1.4% for the 1995–2011 period). Post-release experiment should thus be carried on and full observer coverage in both oceans should be attained to correctly estimate the impact of the purse-seine fishery on whale sharks.

In conclusion, in the main areas of co-occurrence between whale sharks, cetaceans and the purse-seine fishery (Gabon to Angola, Mozambique Channel and east of Seychelles), the populations present may not highly suffer from the apparent impact of the purse-seine fishery recorded in this thesis. Nevertheless, this impact has to be validated on the longer term, especially for whale sharks, and non-lethal impacts should also be kept in mind. In addition, only impact from European purse-seine fishery has been accounted for. Other fishing fleets (mainly Ghanaian and Seychelles purse-seiners) are also operating in the EAO and WIO (∼30% of the purse-seine tuna catch), and may potentially also perform whale and whale shark associated fishing sets. For these fleets, no data are available on the bycatch and encircled species, as well as on the potential use of "safe-release" methods. Moreover, other areas have also been identified, for both megafauna groups, as potential key areas that should be accounted for in conservation planning. For baleen whales, these include areas inhabited by very small northern hemisphere populations (northwest African coast and Arabian sea) during upwelling (Mauritania and Somalia) periods. As suggested above, the size of these populations may explain the very few whale associated fishing sets recorded during the Somalian fishing period (June–November), but potential fishing effort relocation cannot be excluded in case of extended FAD moratoria, and should be kept in mind considering the sensitivity of whales populations in these northern hemisphere areas. For whale sharks, it is clear that calving is occurring in the equatorial mid-Atlantic, as well as potentially off Mauritania. Some small juveniles and pregnant females, potentially more sensitive to encirclement and/or that may have higher impact on the population in case of mortality, may therefore be found in these areas. While less baleen whales and whale shark encirclements by the purse-seine fishery have been registered in these possible key areas compared to the main areas of co-occurrence, conservation measures over these areas may potentially be as equally important. Ultimately, the general decrease in both baleen whales and whale 1.11 6.3) has to be highlighted. These declines may be simply due to the shift in fishing strategies following increasing FAD fishing. But it could also be caused by a decrease in whales and whale shark's populations. This may be especially true for whale sharks, as their encirclements are mostly incidental, and therefore do not completely depend on a fishing strategy (i.e. will be encircled when fishing for free school sets). In addition, it is recognized that whale shark populations are globally declining Theberge and Dearden 2006 Bradshaw *et al.* 2008), which has recently (June 2016) led the IUCN to classify the species as Endangered.

7.1.3 Megafauna species captured as bycatch of the tuna purse-seine fishery

Other megafauna species are also incidentally encircled by tuna purse-seine nets worldwide. These species, smaller in size (sharks, rays and turtles), are however not considered as sighting cues for locating tuna and this time enter the bycatch category, because 1.12). Their catch may also present spatio-temporal variations and differ according to the fishing mode. Most of such species have being classified by IUCN as having a potential extinction risk but the risk's degree 7.1). For instance, the silky shark, the megafauna species the most encountered in all fishing modes (Chapter 5) is classified as Near Threathened. On the other hand, hammerhead sharks (*Sphyrnidae* 7.1) or the oceanic whitetip shark (*Carcharhinus longimanus*), second most abundant shark taxa in the EAO and WIO, respectively, are classified as Endangered or Vulnerable. Similarly the most common turtle species, the olive ridley sea turtle (*Lepidochelys olivacea*) is classified as Vunerable, while some other species such as the leatherback turtle (*Dermochelys coriacea*) or the Hawksbill turtle (*Eretmochelys imbricata*) are classified Critically Endangered. Finally, rays encircled in purse-seine nets include pelagic stingrays (Least Concerned), manta and mobula rays (Near Threatened to Endangered). It should be stressed that some of these purse-seine bycatch Amandè *et al.* 2011 Filmalter *et al.* 2013 Tolotti *et al.* 2015b) or marine Bourjea *et al.* 2014). Other species, on the other hand, are still lacking specific Croll *et al.* 2015) or hammerhead sharks.

Firstly, the most abundant megafauna taxa captured by the purse-seine fishery is the silky shark. Concern about this species, highly captured in longline and purse-seine fisheries worldwide, have been formulated following decline in bycatch rates and captured Clarke *et al.* 2011 Hutchinson *et al.* 2013 Rice and Harley 2013). Silky sharks are mostly captured on FAD sets and also get entangled in FADs' netting, which often Amandè *et al.* 2010 2011 Filmalter *et al.* 2013). In this thesis, it was also evidenced that silky shark is the most abundant bycatch taxa in whale and whale shark associated sets in the EAO and WIO (Chapter 5). It should however be mentioned, that mostly juveniles are caught on FAD sets, while larger individuals (including adults) are caught on free school, whale and whale shark associated sets. As discussed in Chapter 5, there is an inter-ocean difference in the occurrence and abundance of silky shark bycatch among fishing modes. In the WIO, silky shark bycatch are mostly captured in FAD sets (present in 70% of the positive sets, ∼15% for megafauna associated sets and 6% for free

school sets), with an average of 7–9 (± 0.3–3.3) individuals per set when present. In the EAO, silky shark occurrence at FAD and whale associated sets were this time similar (23–27% of the sets) and higher than free school and whale shark sets (7–8%), with higher number of individuals on megafauna associated sets (24 ±5.8 individuals in whale associated sets and 4 ±0.3 in FAD sets).

Table 7.1 IUCN status of bycatch megafauna species and main encircled megafauna species (whale shark and baleen whales) in the tropical tuna purse-seine fishery from the eastern Atlantic and western Indian Oceans. Species have been classified, among groups, by status.

	Scientific name	**Common name**	**IUCN status**
Sharks	*Rhincodon typus*	Whale shark	Endangered
	Sphyrna lewini	Scalloped hammerhead	Endangered
	Sphyrna mokarran	Great hammerhead	Endangered
	Alopias vulpinus	Common tresher	Vulnerable
	Carcharhinus longimanus	Oceanic whitetip	Vulnerable
	Sphyrna zygaena	Smooth hammerhead	Vulnerable
	Isurus oxyrinchus	Shortfin mako	Vulnerable
	Carcharodon carcharias	Great white	Vulnerable
	Carcharhinus falciformis	Silky shark	Near threatened
	Carcharhinus leucas	Bull shark	Near threatened
	Galeocerdo cuvier	Tiger shark	Near threatened
	Megachasma pelagios	Megamouth	Least concerned
	Prionace glauca	Blue shark	Near threatened
Rays	*Mobula mobular*	Giant Devilray	Endangered
	Manta alfredi	Reef Manta ray	Vulnerable
	Manta birostris	Oceanic Manta ray	Vulnerable
	Mobula japanica	Spinetail Devilray	Near threatened
	Pteroplatytrygon violacea	Pelagic stingray	Least concerned
	Mobula tarapacana	Chilean Devilray	Data deficient
Turtles	*Dermochelys coriacea*	Leatherback	Critically endangered
	Eretmochelys imbricata	Hawksbill	Critically endangered
	Lepidochelys kempii	Kemp' turtle	Critically endangered
	Caretta caretta	Loggerhead	Endangered
	Chelonia mydas	Green turtle	Endangered
	Lepidochelys olivacea	Olive ridley	Vulnerable
Whales	*Balaenoptera borealis*	Sei whale	Endangered
	Balaenoptera physalus	Fin whale	Endangered
	Megaptera novaeangliae	Humpback whale	Least concerned
	Balaenoptera edeni	Bryde's whale	Data deficient

In the WIO, as silky sharks are mostly captured in FAD sets (in terms of occurrence and abundance), the main areas and period with high silky shark bycatch corresponds to the 7.4). These spatio-temporal strata are i) outside and along the Somalia EEZ from 0 to 10°N during SW and INE monsoons and ii) north-west waters [1] Amandè *et al.* 2011). In contrast, in the

[1]The temporal variability in main bycatch areas has not been assessed by Amandè et al. (2011), the periods mentioned corresponds to the FAD fishing periods in these areas.

EAO, the same dedicated analysis of main silky shark bycatch area has not been performed. However main shark bycatch areas in FAD sets (i.e. mainly silky shark) are off Senegal to [2] Torres-Irineo *et al.* 2014). In free school sets main shark bycatch areas (hammerhead and silky sharks) are off Guinea (seasons Torres-Irineo *et al.* 2014). This has not been investigated for whale and whale shark associated fishing sets, but it should be noted that one of the main shark bycatch area at FAD corresponds to the area and period with higher megafauna associated fishing sets in the EAO (Gabon). This not being the case in the WIO, it might explain the inter-ocean difference previously mentioned, with similar silky shark occurrence at FAD and whale associated sets in the EAO.

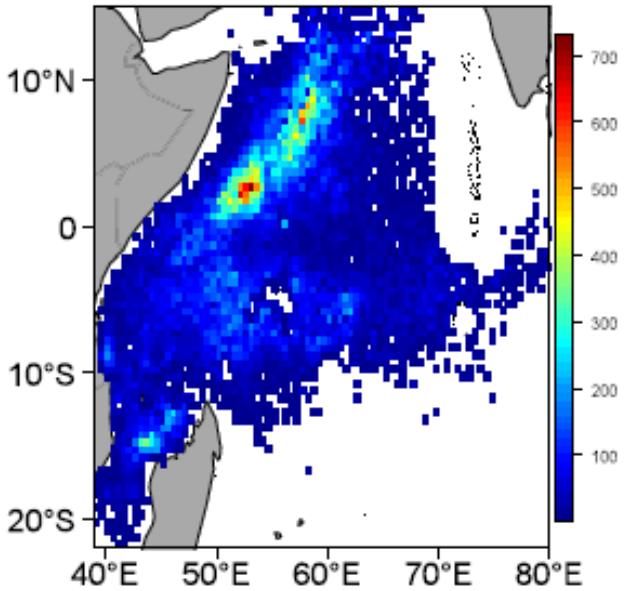


Figure 7.4 Total number of silky shark bycatch in FAD sets over the 2003–2009 period from French Amandè *et al.* 2011).

Recent studies found that the overall fishery induced mortality on silky shark was high Poisson *et al.* 2014a Hutchinson *et al.* 2015). Many individuals were already dead when brought onboard, due to compressed and anoxic conditions in the sack and during brailing. To the contrary, individuals meshed in the net and brought onboard during the hauling process have higher chances of survival (18% mortality rate), but this involve few individuals compared to the number brailed onboard. Therefore bycatch mitigation measures have being investigated to let sharks escape before being in the sack Dagorn *et al.* 2012b Itano *et al.* 2012). In addition, safe release methods, for all shark species, once onboard have also being developed and European crews have been trained Poisson *et al.* 2014b). Finally, as silky sharks have been found to get entangled in FADs' netting, non-entangling FAD (rolled nets or ropes) have also been developed and have Dagorn *et al.* 2012b Poisson *et al.* 2014a Goujon

[2]Similarly, the periods mentioned corresponds to the FAD and free schools fishing periods in these areas.

et al. 2015). Overall, detailed studies are still lacking, especially in the EAO, or for all fishing modes, for this abundant bycatch species. When brought onboard, the purse-seine fishery has a relatively high impact of silky sharks, which highlighted the need to develop mitigation measures.

Secondly, oceanic whitetip shark, the second most abundant shark bycatch species in the WIO, is also mostly captured on FAD sets. This species is among the three most common pelagic shark species, along with silky and blue sharks, yet it has generally been less studied. While data and monitoring are still lacking, populations are worldwide considered to be Rice and Harley 2012 Tolotti *et al.* 2015a). In the purse-seine fishery, it has Tolotti *et al.* 2015b) as in comparison bycatch rates are relatively low and dispersed in the EAO (<2% of sets with oceanic whitetip shark bycatch). Similarly to silky sharks, they are mostly captured on Tolotti *et al.* 2015b) but also occur in other fishing modes (Chapter 5). The main areas and periods of oceanic whitetip occurrence are i) east of Seychelles during NE monsoon and ii) off Kenya and 7.5). Therefore, oceanic whitetip 1.10), but unlike silky sharks, higher occurrences do not appears to correspond to main FAD fishing areas and periods. Finally, post-capture survival has not being investigated, but is likely to be similar among sharks' species for similar release procedures (i.e. entangled or brailed). Therefore, when assuming relatively high mortality rates (i.e. similar to silky sharks) of the purse-seine fishery the species may also benefit from the development of mitigation measures and safe release methods.

Thirdly, regarding sea turtles, when considering species altogether, bycatch rates are relatively balanced between FAD (0.05 individual per set) and free school (0.04) sets in the EAO while rates are higher on FAD (0.05 compared to 0.01 individuals per free school Bourjea *et al.* 2014). In both oceans, the most encountered species are Kemp's and olive ridley turtles, the first one being classified as "Critically Endangered", 7.1). It should however be mentioned that both species are within the same genius (*Lepidochelys sp.*), very difficult to differentiate and the distribution range of Kemp's turtles in the EAO was considered not to include the Bourjea *et al.* 2014) therefore suggested possible misidentification of this species with olive ridley turtles, which could easily be verified using DNA samples of captured individuals. Following these two species, loggerhead and leatherback turtles in the EAO, and hawksbill and green turtles in the WIO, are also relatively Bourjea *et al.* 2014). The three first species have been

7.1), which therefore make them the most at risk bycatch or encircled megafauna species in tuna purse-seine fishery.

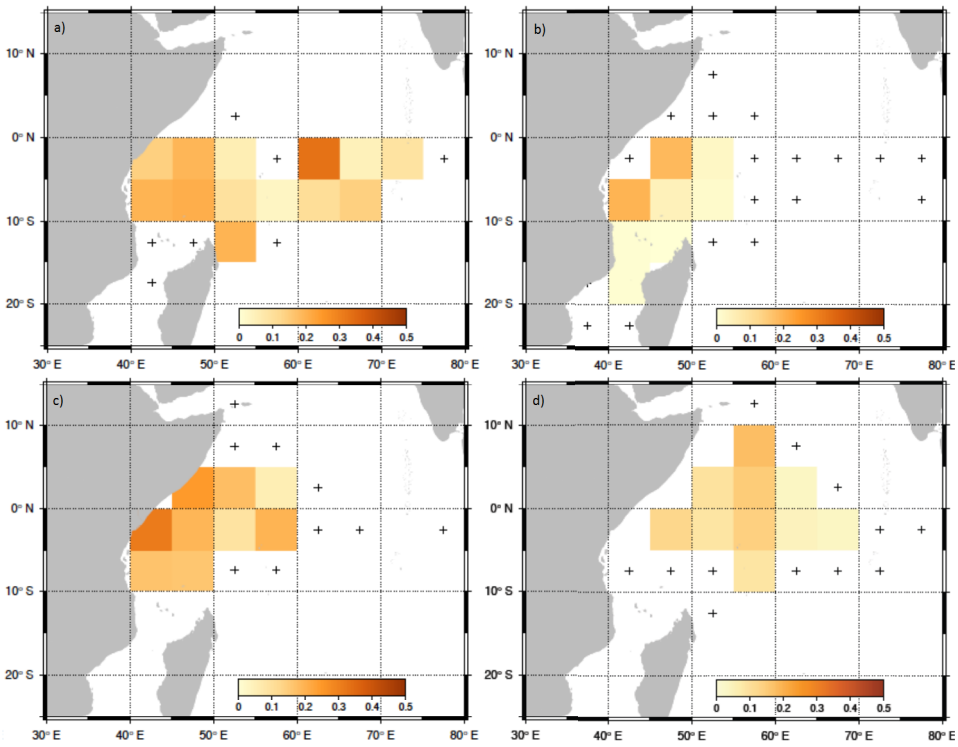


Figure 7.5 Oceanic whitetip shark occurrence as bycatch in FAD sets in the western Indian Ocean (French observer data 1995–2014) per quarter (1 to 4, almost corresponding to a) NE, b) ISW, c) SW and d) INE monsoon periods). Scale correspond to the proportion of FAD sets with oceanic whitetip Tolotti *et al.* 2015b).

The investigation of spatio-temporal variation in main areas of turtle bycatch per FAD and free school sets revealed interesting patterns per species and fishing mode. First, in the EAO, higher sea turtle bycatch per fishing set occurs i) in the coastal area of Gabon to northern Angola during seasons 2 and 3 and involve Kemp's and Olive Ridley turtles on both FAD and free school sets, and ii) off Guinea-Bissau and Guinea (leatherback) and 7.6).

However, for both fishing sets, there are also some bycatch widespread throughout all fishing areas and seasons. Second, in the WIO, higher sea turtle bycatch per fishing set occur i) outside but along the Somalia EEZ, especially in the northern part, during SW and INE monsoons on FAD (mostly Olive Ridley), ii) north-west Madagascar during NE and ISW 7.6). The

major difference between oceans is that most areas with high bycatch rates are close to shore in the EAO, while they are in the open ocean in the WIO (apart from the Mozambique Channel). In addition, mostly adults are caught in the EAO, mainly in coastal areas (except Bourjea *et al.*,

2014). Juvenile sea turtles mostly occur offshore, drifting with currents. This therefore explains why they are less encountered in the EAO, as strong currents carry away juveniles Monzón-Argüello *et al.* 2010). In addition, offshore juveniles might tend to look for protection, food or rest site under FAD rather than just drifting, also explaining the higher occurrence in FAD sets in the WIO.

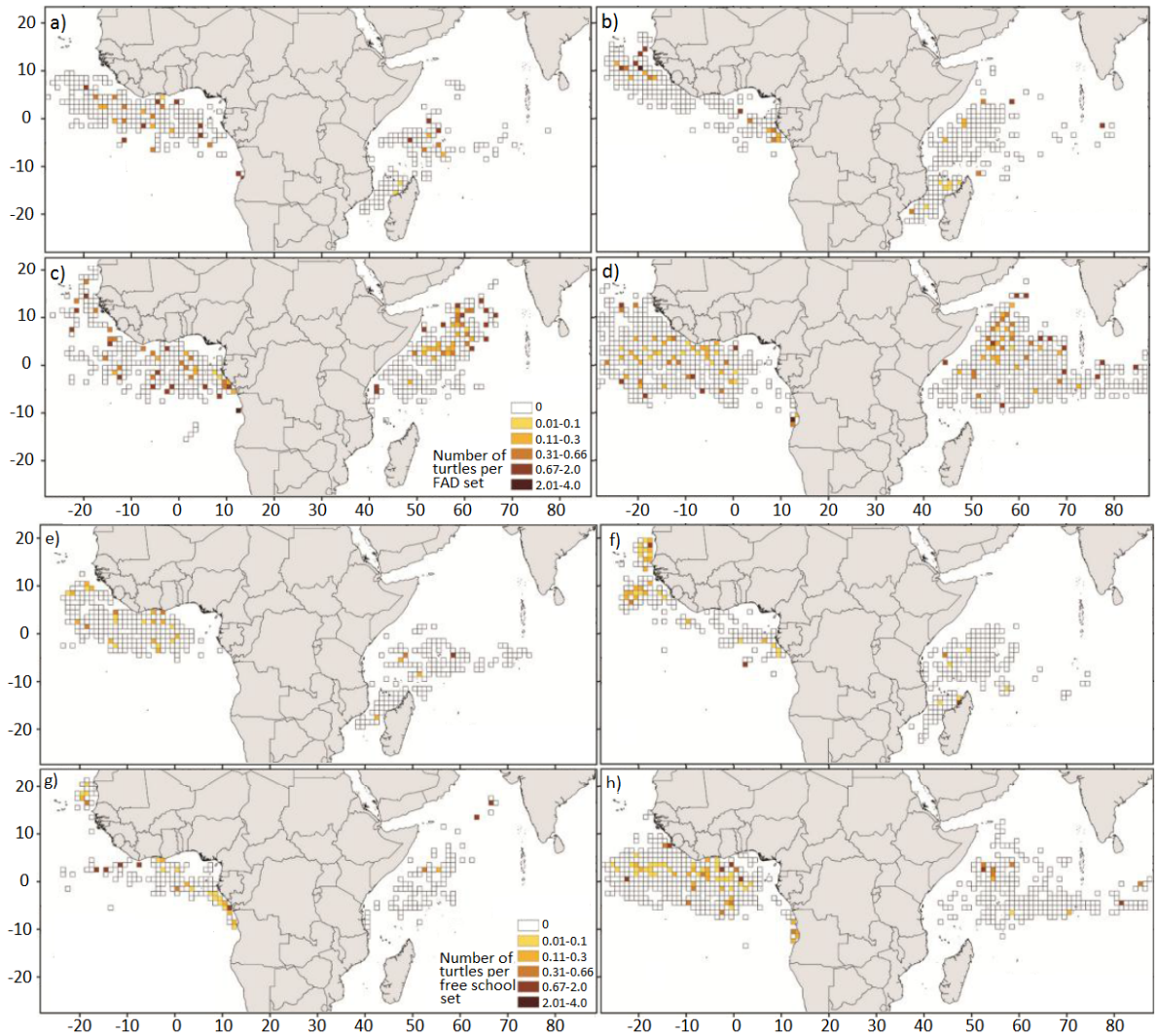


Figure 7.6 Number of turtles captured per FAD (a, b, c and d) and free school (e, f, g and h) sets in the eastern Atlantic and western Indian Oceans per quarters (French and Spanish observer data Bourjea *et al.* 2014).

In both oceans, the sea turtles apparent survival when encircled or entangled in FAD's Bourjea *et al.* 2014). However, this is upon release, no studies, to our knowledge, have investigated the post-capture survival of turtles on the longer term. In addition, turtles entangled in FADs' netting only included the ones noticed by observers (i.e. in the upper part of the netting) and

thus did not accounted for ghost fishing. Finally, it has been emphasized that turtles bycatch varies between oceans, fishing mode and species. The apparent impact of the purse-seine fishery appears relatively low but this needs to be confirmed in the longer term.

Finally, other vulnerable megafauna species are also captured as bycatch in purse-seine fishing sets but lack dedicated studies. This is for instance the case of hammerhead sharks, second most abundant shark bycatch taxa in the EAO, as well as manta and mobula 7.1). For both megafauna groups, the few available information come from general Romanov 2002 Amandè *et al.* 2008 2010 Torres-Irineo *et al.* 2014). Hammerhead sharks appear to be mainly captured in the EAO, as few individuals have been recorded in the WIO, and on FAD sets. Likewise, manta and mobula rays also

Croll *et al.* 2015) but mostly on free school sets, while in the WIO their bycatch occur in both FAD and free school sets. Further investigation should be made to confirm these results, especially in the WIO, and to study spatio-temporal variation in bycatch rates for both species Amandè *et al.* 2008) found apparent mortality rates of 40% for manta and mobula rays. It is however likely that this would include some individuals still alive but that might not survive in the next few days (i.e. release using ropes through gill slits). Indeed at this time, no advices had been formulated on good practices to release megafauna species. Therefore higher effective mortality rates may be expected for that period, but also nowadays as such practices may still be sometimes used.

Overall it is clear that several bycatch species are impacted by the purse-seine fishery. Yet, even for the most abundant megafauna bycatch species, the silky shark, few studies exist in the EAO. In addition, some species, although less abundant in fishing sets are classified as Endangered and Critically Endangered by IUCN and may therefore benefit special focus. Apart for the silky shark for which longer term post-release survival rates have been investigated, only apparent survival rates recorded by scientific onboard observer exist. This may therefore limit correct assessment of fishery impact on populations. Based on available maps of main bycatch areas per taxa, it can be showed that some regions and periods of higher bycatch rates are shared by several megafauna species or groups. This is the case for the Gabon to Angola coastal area (April–September) in the EAO. As mentioned previously, both baleen whales and whale sharks co-occurence with the purse-seine fishery are high, as well as shark bycatch (mostly silky shark, but maybe hammerhead sharks as well) and Kemps' and olive ridley sea turtles. In addition, in this ocean, two other areas have high sharks (silky and hammerhead sharks) and endangered turtles (leatherback or loggerhead) bycatch on free school sets in season 2: i) within the Mauritania EEZ (loggerhead) and ii) off Guinea (leatherback; the area being known for having nesting sites). This stratum (Cape

Verde and Mauritania to Guinea during seasons 1 and 2) also presents mating and calving grounds for northern hemisphere baleen whales, including an endangered population of humpback whale. Likewise, same patterns could be distinguished in the WIO but would mostly correspond to seasons of high FAD fishing. Therefore, higher bycatch rates of i) silky sharks and olive ridley turtles occur outside but along the Somalia EEZ during SW and INE monsoons and ii) silky sharks and hawksbill turtles occur north-east of the Mozambique Channel during NE and ISW monsoons.

7.1.4 Conservation of vulnerable megafauna species: case study of the tropical purse-seine fishery in the eastern Atlantic and western Indian Oceans

From the main findings of this thesis and a short review of literature of the current knowledge of megafauna species bycatch presented in the previous section, a general picture of encircled and bycatch megafauna in the tropical purse-seine fishery can be drawn. For all species, it has been demonstrated the existence of a strong spatio-temporal variability. Such characteristic is mostly linked to factors such as high productivity and key reproduction areas (mating, calving or nesting grounds) in the EAO, while in the WIO, it mostly follows fishery seasonality (also linked to productive areas), especially FAD fishing for bycatch species. It can be noted that monsoon seasonality (reflecting fishing effort distribution in time and space) was one of the main variables linked to the co-occurrence between whale sharks, cetaceans and the fishery in the WIO (Chapter 4). In addition, simulations of large FAD moratoria showed reduction in all bycatch species in the WIO, while more contrasted results with some bycatch groups increasing in the EAO (Chapter 6). This suggests that conservation measures for vulnerable megafauna species may therefore need to be ocean-specific.

First of all, it is important to mention striking differences between the two oceans in terms of monitoring and conservation of encircled and bycatch megafauna species. In the WIO, both cetaceans and whale sharks intentional encirclement are prohibited since September 2013 (IOTC res. 13/03 and 13/05). However such measure, to be fully effective, needs to come along 100% observer coverage. This is still lacking in the WIO but has been achieved in the EAO in 2014. However in contrast, apart from the EU cetaceans encirclement EU 2007), no ICCAT megafauna set ban exists in this ocean. Full observer coverage while sought by European vessel owner companies (e.g. OCUP "Observateur Commun Unique et permanent" program for French purse-seiners) cannot be achieve in the WIO due to piracy risk and the necessity of military guards onboard vessels, leaving no space on most vessels for observers. Electronic observers (onboard video camera) are currently

Ruiz *et al.* 2015) and have started to be installed in some vessels lacking scientific onboard observers, which may allow reaching 100% observer coverage. Until then, we cannot exclude possible under-reporting of whale and whale shark associated sets by skippers in the WIO. This appears not to be the case for whale associated sets (but cannot be validated without full observer coverage), as the three sets reported by skippers in 2014 6.3) were also recorded by scientific observers (effective encirclement of the whales). In opposite, the two whale shark associated fishing sets recorded by observers in this ocean in 2014 were not reported in logbooks. This is counter intuitive because most baleen whale associated sets are intentional, which is prohibited, one could thus expect that this fishing mode would be under-reported, as well as that skippers would avoid baleen whales when an observer is onboard (i.e. "observer effect"). On the contrary, in general whale shark associated sets are accidental, with individuals only seen once the purse-seine net has been set. In this case the IOTC regulation requires that all the steps to ensure safe release of the individual should be taken. Therefore, either whale shark associated sets are accidental or they are intentional and crews may avoid mentioning the whale shark before setting so that the observers believe it is accidental. Either way, we would expect whale shark associated sets to be more often declared than whale associated sets. Consequently, full observer coverage should also be reached in the WIO to correctly assess rates of interactions between purse-seine fishery and megafauna species.

Second, it is logical to consider that whenever possible, avoiding encirclements of megafauna species would limit the potential impact of the purse-seine fishery on these species. Similarly, for vulnerable bycatch megafauna species, avoiding deck landing of individual will reduce mortality rates. This is especially important for shark species, which have been shown (on silky sharks but may be similar in other shark species) to have very low survival rates (<20%) when they are brought onboard (except when meshed and released Hutchinson *et al.* 2015). Therefore mitigation measures are currently investigated to release sharks (mainly silky sharks) during the hauling of the net (e.g. release panel, Dagorn *et al.* 2012a Itano *et al.* 2012 Restrepo *et al.* 2016). Similarly, in the eastern Pacific Ocean (EPO), the development of mitigation measures (gear and setting methods modification) permitted the drastic reduction Hall 1998).

Third, when animals are brought onboard or encircled, good practice methods to 2.3), rays and turtles have been Poisson *et al.* 2012 2014b Escalle *et al.* in press). For whale sharks and humpback whales (same method than whale sharks) encircled in the sack, these safe release methods have been undertaken by European purse-seiners' crews

(Chapter 2). However observers have also noted that possibly harmful methods (e.g. skiff towing whale shark and humpback whale by the tail or the flippers) are still used nowadays (observers data and pictures). For bycatch megafauna species, handling practices to promote individual survival and reduce risks to the crew, as well as practices to be avoided, are Poisson *et al.* 2012). These handling practices could potentially be easily implemented onboard purse-seiner for turtles and rays, especially small individuals, as there is low risk for the crew and they do not take extensive time, but detrimental practices have still been observed nowadays for manta and mobula rays (observers data and pictures). However, for sharks, especially large ones, handling practices to promote individuals survival may need time so that the crew safety is maintained and thus could potentially be less used (observers data and pictures, field work onboard). Furthermore, it should be noted that observers record the fate of the individuals in terms of i) discarded (release or escape for encircled megafauna) alive, ii) discarded dead, iii) or kept onboard (not applied for megafauna). Interestingly, in the WCPO observers also have to record, for species of particular interest (sharks, rays, turtles, cetaceans) individuals' condition upon release, such as i) alive and healthy, ii) alive but injured or distressed, iii) alive but unlikely to live, iv) alive unable to describe condition, v) entangled but ok, vi) entangled injured, or WCPFC 2014). Such additional information may help estimating precise survival rates upon release, especially in the absence of longer term post-capture survival rates.

In parallel to these mitigation measures for encircled and landed on deck megafauna species, which are currently under development and encouraged, some regulation may be implemented in order to avoid areas of high bycatch or encirclements of sensitive species. For instance in the EPO, fishery closure areas to reduce silky sharks bycatch without causing Watson *et al.* 2009). While defining small (∼5° square) areas were not efficient (i.e. they represented low silky sharks bycatch), higher closure areas (20°x9°) could reach an optimum reduction of 25% of silky sharks bycatch and only reducing 9% of the tuna catch. Similar method could be used to investigate spatio-temporal closure to limit bycatch of endangered species in the EAO and WIO.

In the EAO, areas already identified for having higher bycatch rates of leatherback and loggerhead sea turtles (i.e. off Mauritania and Guinea during season 2), also matching higher silky and hammerhed sharks bycatch rates, could be investigated. They are relatively small in size and covered only one season (detailed investigation might even identify shorter periods). Until now, data were still lacking for rare and vulnerable megafauna species, however with the full observer coverage since 2014 in the EAO, we should expect that bycatch data will be less scarce in the future. In addition, the Gabon to Angola coastal area (seasons 2 and 3) also presented high sharks and some turtle species bycatch rates,

as well as whale and whale shark associated sets, which could also represent a potential closure area that may benefit several vulnerable species. However this productive area 6.10 6.11). Details investigation is thus needed to verify i) which shark species are captured in this area (nowadays only global shark bycatch estimation is available), ii) if the Critically Endangered Kemps' turtle is in fact present in this area or if it has been mistaken for olive ridley turtles. Concerning baleen whales and whale sharks in this area, if we consider that ii) non-lethal impacts of whales encirclements are low, and ii) whale sharks post-encirclement survival rates following safe release method are high, there is no reason for considering conservation management measures for these species in this area. Crews should nevertheless be incited to use safe release methods for encircled whale sharks, as well as humpback whales (few cases of encirclements have also been recorded for this species). Nevertheless, as mentioned previously, northern hemisphere baleen whales populations may possibly be more impacted by the purse-seine fishery, due to the very small populations sizes. Similarly, fishing sets in whale shark calving areas may lead to encirclement of pregnant females and neonates or small juveniles, which may be more sensitive to encirclements or have higher impact on the population in case of mortality. Therefore conservation measures over these spatio-temporal strata may be important for these species, without highly impacting the fishery as few whale and whale shark associated sets occur in these areas and periods. Finally, in this ocean, as most bycatch and encircled megafauna main areas are within EEZ (i.e. Gabon and Sumaila *et al.* 2007), the current proposition of some NGOs and scientists to close the high sea to fishing White and Costello 2014) may increase fishery impact on megafauna species and have deleterious effects on populations.

Amandè *et al.* 2011 Bourjea *et al.* 2014). It is therefore strongly likely that regulations to reduce FAD sets will also have positive effects on bycatch. This is not the case for encircled megafauna species (Chapters 2 and 3), but as mentioned previously both whale and whale shark intentional encirclements are already prohibited in the WIO. Identification of main objectives of a given regulation is primordial before its implementation. Nowadays in spite of the general adoption of the EAF management's principle, bycatch and ecosystem components are still lacking within objectives (even secondary) of regulations toward tuna stocks. A key element is also to be able to forecast possible side effects that may come along a regulation. Hence, in Chapter 6, we have investigated the potential consequences of fishing effort regulation and conservation measures. In particular, large six-month FAD moratoria have been simulated. In the WIO, an annual reduction of ∼17% of FAD sets would lead to the

general reduction in all bycatch species (between 1% and 25% (sharks) depending on the group and the fleet considered), but also in total tuna catch (6% for the French fleet and 17% for the Spanish fleet). Therefore, even with fishing effort relocation to non regulated areas, the impact for the purse-seine fishery of such measure could be significant. Hence, it is unlikely that IOTC will implement such a long moratorium in the main FAD fishing period and area. In addition, main bycatch areas of some species at risk (oceanic whitetip shark, Kemp's and hawksbill turtles) are within unregulated areas. However, some other interesting propositions to limit the impact of FAD fishing have also started to be raise. Indeed, it has been proved that bycatch/catch and number of silky shark/catch ratios decrease with the Dagorn *et al.* 2012a). This indicates that FAD sets with large tuna catch will have a smaller bycatch/catch ratio, while sets with small catch (especially <10t) will have larger bycatch/catch ratio. Therefore it has been suggested that regulations inciting fishers to mostly set on FAD with large tuna school (reliable estimation from skippers prior setting, which is also enhanced by echo-sounder buoys) could effectively reduce bycatch rates without impacting tuna catch. This could be reached through different regulations: Davies *et al.* 2014), or ii) reward fishing Dagorn *et al.* 2012a). Such aspects would be particularly interesting in the current atmosphere of discard ban (IOTC res. 15/06). Nevertheless, as the catch of tuna would not necessarily be reduced, to prevent overfishing of yellowfin and bigeye, such measure would need to come along regulations that could limit the catch of targeted tunas. Currently in both oceans, FAD limitation have started to be implemented with a limit of 550 and 500 active buoys per vessel in the WIO (IOTC res. 15/08, updated to 425 in 2016) and EAO (ICCAT REC [15-01]), as well as measures toward supply vessels (i.e. supply now has to be shared by at least two vessels). Other regulation measures could also be investigated, such as catch quota per species and per size classes (i.e. juveniles vs adults for yellowfin and bigeye tunas) and/or by limiting the fleet capacity (e.g. number and size of the vessels). Finally, to reduce other ecological impacts on tuna stocks (possible ecological trap), bycatch (ghost fishing) Maufroy *et al.* 2015), the reduction of the total number of FAD sets, the utilization of biodegradable and non-entangling FAD, as well as FAD deployment area closure should also be considered.

Biodiversity may also be viewed as an important aspect to take into account in an EAF. The CBD recognize several biodiversity indices such as i) species richness and evenness, including emblematic or keystone species, ii) genetic diversity to increase species resilience, CDB 1992). This also falls within the "Good Environmental Status" of the EU, which aims to

maintain biological diversity, marine food webs and sustainable exploited fish stocks. In this thesis, when investigating diversity, due to the type of data used and the low number of megafauna associated sets i) it only included bycatch and ii) only diversity in terms of species composition, richness and evenness was investigated. While areas with high bycatch diversity may appear as of high conservation importance (e.g. off Somalia and the Lezama-Ochoa *et al.* 2015), phylogenetic and functional diversity should also be investigated. Indeed, several species in these "hotspots" of high diversity may have the same function in ecosystem or be closely related. On the contrary, other areas with less species may present several key ecosystem functions and/or various evolutive histories, and even include endemic or rare taxa. Complementarily, it has recently been suggested that in an objective of maintaining ecosystem structure and functioning, selective fishing may not be the best management measure, as it may impact food webs Rochet *et al.* 2011). In this way, balanced harvest concept has emerged as a new approach Garcia *et al.* 2015). It aims at reducing ecological effects of fishing by avoiding unbalanced removal of some components of the ecosystem and therefore to distribute fishing mortality to the widest possible range of species, stocks and sizes in an Garcia *et al.* 2012). To what extent this should include vulnerable and emblematic megafauna species is still currently debated. In addition, applying balanced harvest concept to the purse-seine fishery may be limited as relatively few targeted and bycacth species are abundantly captured. However this may include maintaining some fishing effort on all fishing modes, as they captured different targeted and bycatch species or sizes. For instance, while FAD fishing should be reduced and the ecological consequences of this fishing mode should be limited, in a balanced harvest management it should not be completely stopped as some sizes or species are mostly captured on FAD sets.

To sum up, to fully assess the impact of the purse-seine fishery on encircled and bycatch megafauna species, full scientific observer coverage should be reached in both the EAO (since 2014) and the WIO. In both oceans, mitigation measures to avoid bringing onboard vulnerable megafauna species, especially sharks, as well as good practices to release them once onboard or encircled should be investigated and/or encouraged. In addition, it has been highlighted that megafauna conservation measures may need to be ocean-specific. In this way, in the EAO spatio-temporal fishery closures could be investigated to limit the impact of the fishery on endangered species or populations without highly decreasing the tuna catch. On the other hand, in the WIO, while intentional megafauna associated fishing sets are already banned, FAD management measures should allow decreasing bycatch for most species.

7.2 Comparison with the eastern and western Pacific Ocean

7.2.1 Whale shark and cetaceans interactions with the purse-seine fishery

7.2.1.1. Dolphin sets and small toothed cetaceans interactions

The setting of purse-seine nets around tuna schools associated with dolphin herds Hampton and Bailey 1999 IATTC 2010). This however mostly occurs in the EPO. Indeed, in this thesis, we have observed very few dolphin sets in the EAO and WIO (Chapter 3). However even historically, when whale and whale sharks associated reached up to 20% of the sets performed each year, dolphin sets in the EPO have always been more abundant. Indeed, over [3] period dolphin sets represented on average 37.2% ±1.3 of the total number of IATTC 2010). During this period, dolphin sets (4000–14000 per 7.7.a) fluctuated with free school sets as the first or second fishing mode the most performed in the EPO, while FAD sets was systematically the least performed fishing mode (24.0 % ±1.2). In the 1980s, following the implementation of scientific observer programs, the dolphin mortality could be more precisely assessed. Based on the mortality per 7.7.b) from the observer dataset, it was estimated that the annual dolphin mortality varied between 20 000 and 140 000 individuals between 1979 and 1992. The total dolphin mortalities however sharply decreased in the early 1990s to less than 2000 per year, 7.7.b).

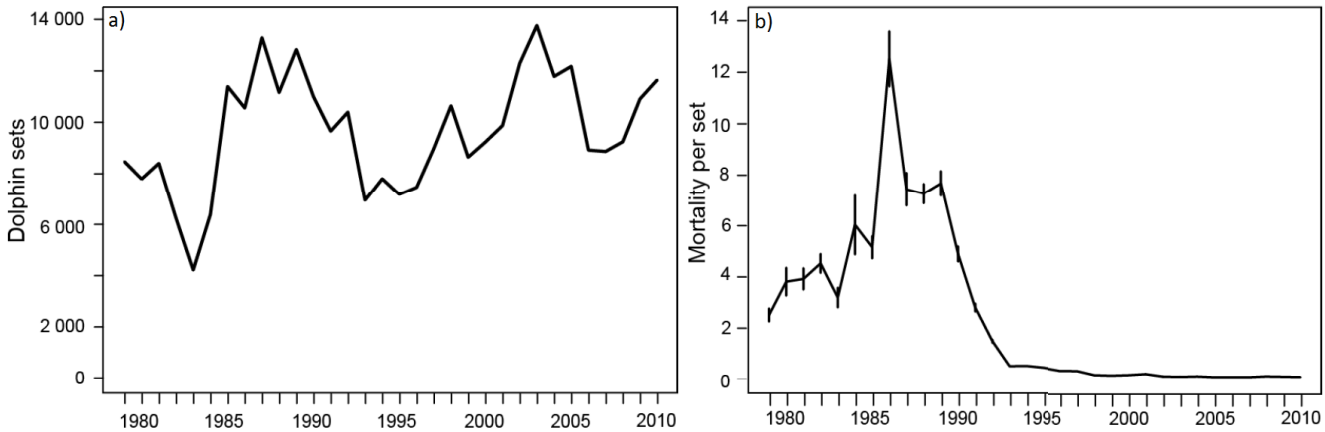


Figure 7.7 Number of dolphins sets performed per year in the eastern Pacific Ocean (a) and average IATTC 2010).

Dolphin sightings are relatively widespread, for each season, over the purse-seine 7.8). On the contrary, dolphin sets, while been more

[3] Last available annual report of IATTC is of 2010 (IATTC 2010).

abundant during season 1, are relatively localized in the same productive areas year-round: 7.8 and Appendix 7.A.1). In addition, in season 1 high number of dolphin sets is made off Nicaragua to Mexico, and 7.8).

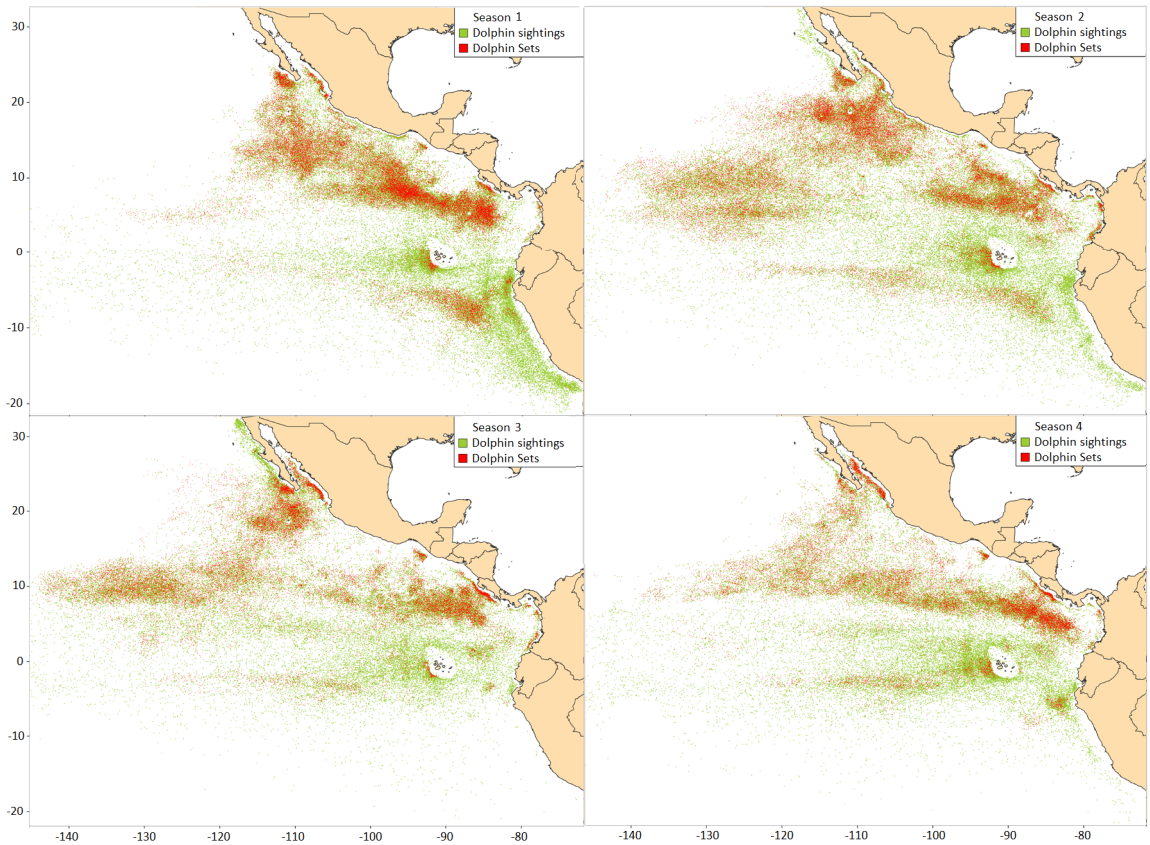


Figure 7.8 Spatio-temporal distribution of dolphin sets and sightings recorded by scientific observers per season (four quarters) in the eastern Pacific Ocean over the 2005–2015 period (Marlon Roman (IATTC), personal communication).

In the western and central Pacific ocean (WCPO), 0.4% of the sets recorded delphinids interactions with purse-seine vessels (i.e. one or more individuals fully or partially encircled in the net) in the 2007–2010 period (observer data, 16 and 45% fishing days coverage in WCPFC 2010). This corresponds to a total of 917 individuals (within 159 fishing sets). While being lower than in the EPO, it is higher than in the EAO (0.07% of the sets with dolphin associated for the 1980–2011 period) and WIO (0.03%). Similarly, the mortality rate was relatively high with 60% over the 2007–2010 WCPFC 2010). The species involved are mostly false killer whale (*Pseudorca crassidens*) and several species of dolphin (including bottlenose dolphin (*Tursiops truncatus*), common dolphin (*Delphinus delphis*), indo pacidifc bottlenose dolphin (*Tursiops aduncus*), risso's dolphin (*Grampu griseus*) rough-toothed dolphin (*Steno bredanensis*) and spinner

dolphin (*Stenella longirostris*)) and short finned pilot whale (*Globicephala macrorhynchus*). 7.9) but no information regarding temporal variability was available. It should be noted that no specific fishing mode exist for small toothed cetaceans in WCPFC databases, but interactions are recorded depending on the other cue sighted (FAD, free school, whale or whale shark associated sets). Therefore most interactions (80%) have been observed in FAD sets (anchored WCPFC 2010). Rough-toothed dolphins has been identified as the only cetacean Pitman and Stinchcomb 2002 Hall and Roman 2013). However it is clear that in the WCPO, interaction refers to encircled (partially or totally) individuals. Therefore, it is likely that other species may sometimes visit FAD (including anchored FAD), possibly mostly in the Pacific Ocean. This should therefore be investigated. In the EAO and WIO small toothed cetaceans (false killer whale, short finned pilot whale, pygmy killer whale, Risso's dolphin or melon headed whale) are sometimes observed around the seine during the hauling and bailing process (scientific observer, unpublished data), but it is unlikely to be the case here as interactions refer to encircled individuals.

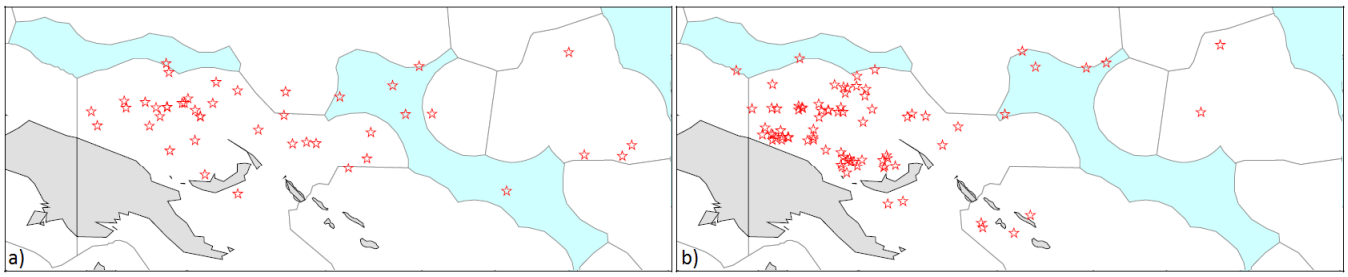


Figure 7.9 False killer whale interactions (a) and dolphins interactions (b) recorded by scientific WCPFC 2010).

Overall, dolphin sets still represent almost half the fishing sets performed in the EPO but dolphin mortality has been highly reduced (<0.1 dolphin per set). In the WCPO, interactions between small toothed cetaceans and the purse-seine fishery have also been recorded in proportion considerably lower than in the EPO but higher than in the EAO and WIO. However, in the WCPO most of these interactions included false killer whales and other small cetaceans in FAD sets.

7.2.1.2. Whale and whale shark interactions

In both the EPO and the WCPO, whale and whale shark associated sets have been Hall *et al.* 1999 Hampton and Bailey 1999). Still, information on baleen whales and whale sharks were generally lacking in the literature for the EPO, results presented

here have been collected directly from IATTC scientists during a two weeks stay at the commission. For the WCPFC, data existed in the literature but were highly fragmented and from several authors and periods. In the WCPO, historic data, up to the 1970s could be found Matsunaga *et al.* 2003 Molony 2005), but the observer coverage and the format of the data vary, so results will often be presented by period. For recent years, the observer coverage rate was of 16% of the fishing days between 2007 and 2009, 45% in 2010, and 100% (between 20°N–20°S) since 2011. On the other hand, IATTC has full (100%) observer coverage since Hall 1998). In addition, the way each tRFMOs considers these megafauna associated sets differed from the one presented in this thesis for the EAO and WIO. In the EPO, as previously described in the previous section, most sets are made on dolphin, free school and FAD. Therefore sets made in association with baleen whales, as any cetaceans, are classified as dolphin sets by IATTC (Marlon Roman, personal communication), and will be recorded as such only when the whale is encircled. On the other hand, whale shark sets are not considered as FAD set, but may be classified as any of the three fishing modes depending on the cue for sighting the tuna school. Therefore ∼25% of the whale shark associated sets have been recorded as FAD sets and ∼75% as free school sets. In this ocean, while whale sightings have to be recorded by observers, whale shark sightings are never recorded (Ernesto Altimirano, personal communication). On the contrary, in the WCPO, whales and whale WCPFC 2010): i) if animals were sighted by observers at the time the tuna school was located and thereafter set in their vicinity, the set is classified as whale or whale shark associated sets, ii) whale and whale shark interactions refer to individuals fully or partially encircled. Therefore some individuals may be recorded as both a set and an interaction. However, sometimes individuals may only be seen once the net has already been set (mostly whale sharks), so whale shark interactions may be found in other fishing modes. Finally iii) observers also record sightings during WCPFC 2010). In the following paragraphs, the current knowledge on whale and whale shark interactions with the purse-seine fishery in the EPO and WCPO will be described.

Firstly, concerning whale sharks, it appears that the proportion of whale shark associated fishing sets compared to the other fishing modes is similar in the WCPO to the ones found during this thesis in the EAO and WIO, but is lower in the EPO. Indeed, in the WCPO whale shark sets represented 0.3–0.7% of the total number of sets performed over Molony 2005 WCPFC 2010 Clarke 2015). However this appears to underestimate the actual rate of whale shark associated sets. Indeed, when accounting for both "whale shark set" records and "whale sharks' interactions" in other fishing modes, the total number of whale shark associated sets was of 0.7–1.5% of all fishing sets between

WCPFC 2010 Harley *et al.* 2013). This is therefore relatively close to the rate of whale shark associated sets recorded in the EAO (1.34 %) and WIO (0.77 %) by scientific observers between 1995 and 2011 (Chapter 2). The under-reporting of whale shark sets is a direct indication that in this ocean as well, whale sharks are also often not seen WCPFC 2010 Clarke 2015). However it should be mentioned that, at least in the WCPO, voluntary setting of nets around whale sharks is not that rare (half of the sets based on available data). When the mortality rate was estimated, it was higher than in our study sites (7–14% between 2007 and 2014), with 88 individuals recorded WCPFC 2010 Clarke 2015). Moreover, historic Japanese purse-seine fishing data (1967–2011) showed that temperate (off Japan: 27–45°N) purse-seine fishing had low but twice the percentage of whale shark sets (average 1.6% per year) compared to tropical (7°S–12° Matsunaga *et al.* 2003). The main spatio-temporal areas for whale shark sets was off Japan (30–40°N and 140–150°W) between June and August, corresponding to the end of the upwelling season (see Appendix 7.A.1). In the tropical WCPO, whale shark associated sets and interactions were mostly located in the Papoua New 7.10). However because these areas Harley *et al.* 2013) sightings per unit of effort should be investigated, as presently no clear conclusion can be drawn. The seasonal variation in whale shark sets and interactions was not investigated, but the fishing effort distribution is Williams and Terawasi 2015). It is therefore possible that whale shark interactions with the purse-seine fishery are relatively stable throughout the year. On the other hand, in the EPO the proportion of sets with whale shark encircled was of 0.3% of all fishing sets and mostly declared as free school sets (Marlon Roman, personal communication). Mortality rate also appeared to be very low. In this ocean, whale shark sets were mostly located in the northern coastal area of Peru, 7.11) during season 1. This corresponds to areas of high productivity due to the presence of the permanent upwelling off Peru, but also the period of the warmest SST in the region (23–28° compared to <18° the rest of the year) (Appendix 7). Finally, in both the EPO and WCPO, the sizes of the whale sharks observed WCPFC 2015, Marlon Roman, personal communication).

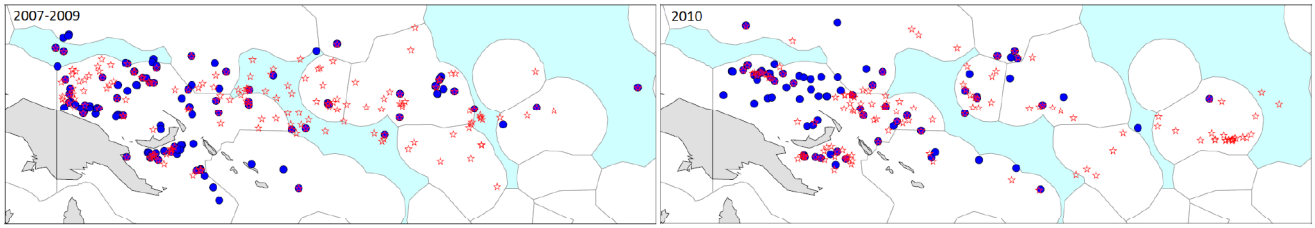


Figure 7.10 Whale shark associated sets (blue circles) and interactions (red star) recorded by observers WCPFC 2010).

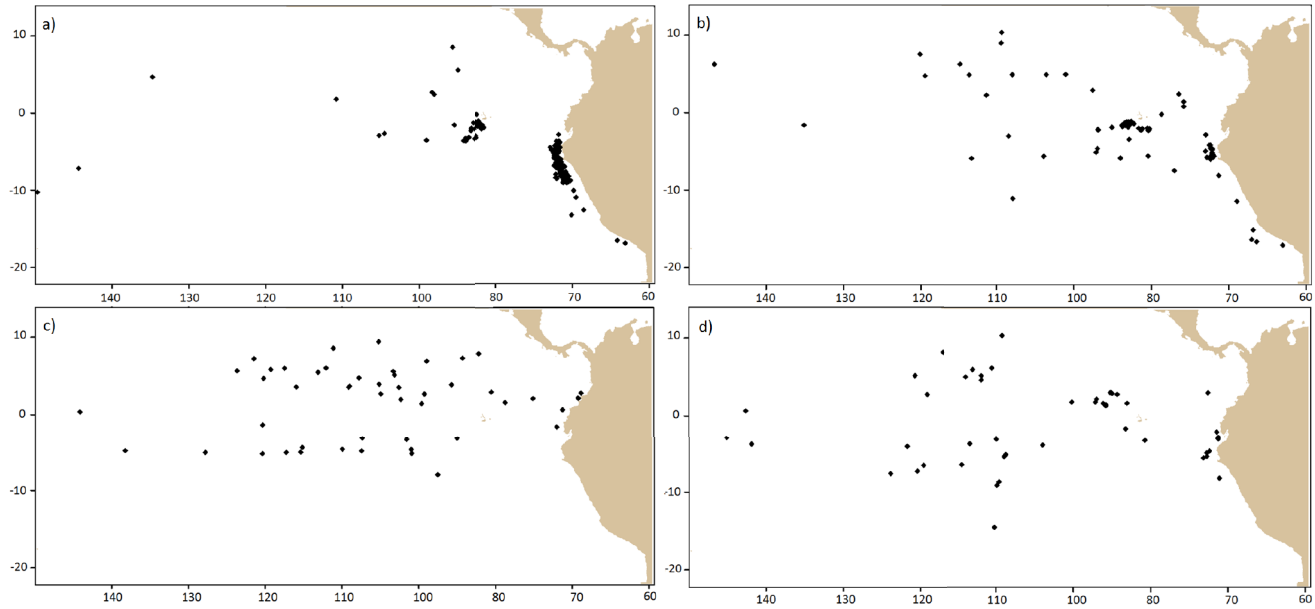


Figure 7.11 Whale shark associated sets recorded by scientific observers per season (a to d corresponding to each quarter) in the eastern Pacific Ocean over the 2005–2014 period (Marlon Roman (IATTC), Personal Communication).

In both regions of the Pacific Ocean, the intentional setting of nets on whale sharks has been prohibited since January 2014 (WCPFC, CMM-2012-04), and July 2014 (IATTC, Res[C-13-04]). While, data presented here do not cover this period, it would therefore be relevant to compare the number of whale shark sets and encirclements prior and after this measure. At the same time of the banning measure, the WCPFC has drafted "safe-release" method guidelines for whale sharks incidentally encircled, similar to the one describe in Chapter 2. However the annual report of observer program reported 149 whale shark interactions in 2014. As the total number of observed sets was not available no conclusion can be drawn on WCPFC 2015). However, it has been noticed that the safe release methods were generally not followed, with small whale sharks often lifted by the tail and sometimes left for extended period of time on the deck, while larger ones are usually pull by the tail by the skiff. Overall 37 individuals were recorded dead (i.e. recorded

WCPFC 2015). In the WCPO, a tagging experiment, on the basis of the one we have implemented in the EAO, has been developed in the early 2015 (Shelley Clarke, personal communication). Observers have been trained and 10 tags (MiniPat and survival PAT) were purchased. However no tagging have been performed since then, presumably due to few whale sharks encircled following the banning regulation (Sheley Clarke, Bruno Leroy, personal communication). Such experiment has not been planned in the EPO yet (Marlon Roman, personal communication).

Secondly, concerning whale co-occurrence and interactions with the purse-seine fishery, rates of whale associated sets where again similar between oceans, yet lower in the WCPO than in the EAO and WIO, and were very rare in the EPO. In the WCPO, it should be stressed that the situation differs from whale shark associated sets, as baleen whales are mostly recorded as an actual set but rarely as an interaction. This suggests that, in agreement to the results found in this thesis (Chapter 3), most whale sets are intentional but individuals are mostly not encircled. Whale associated sets represent 1.6–2.5% of all fishing sets between Molony 2005 WCPFC 2010). It is also noteworthy that skippers, as for whale shark sets, under-reported whale associated sets in logbook, with only 0.1–0.2% WCPFC 2010). The apparent mortality rate was of 6% between 2007–2010, which corresponds to the mortality of two Bryde's whales WCPFC 2010). This is interesting, as in our study only humpback whale mortality has been recorded. In the WIO, the death of a young (potentially more sensitive to encirclements than Romanov 2002). In the WCPO, no information have been given on the maturity stage of the two Bryde's whales recorded dead, but if it involves adult Bryde's whale, this may disagree with our assumption of differing behavior between humpback whale (that may remain within the net until it is captured in the sack) and the other baleen whale species (mostly escaping by themselves by diving or going through the net). In the EPO, sets with large whales (baleen whales and sperm whale) encircled were relatively rare (<0.1%). This might be due to the fact that similarly to the three other ocean basins, baleen whales are rarely encircled even when sets are made in the vicinity of a baleen whale. Therefore, as whale associated sets are not directly recorded as such by observers and may be recorded as free school sets if the whale is not encircled, it is difficult to effectively assess the amount of baleen whales interactions with the purse-seine fishery in the EPO. It is however perceived to be rare and mortality events also appear low or absent (Marlon Roman, person communications). The species involved are similar to the EAO and WIO. Indeed, in the EPO, species involved are fin (45%), Bryde's (22%), blue (8%), sei (8%), sperm (7%) and humpback (4%) whales. While in the WCPO, it is mostly humpback WCPFC 2010 Molony,

2005). Finally, intentional whale associated set has been banned in the WCPO since January 2013 (CMM-2011-03) but not in the EPO, as very few sets are recorded. In both the WCPO and EPO, main areas of co-occurrence between whales and the purse-seine fishery were similar to whale sharks ones. In the WCPO, it was mostly in the Papoua New Guinea EEZ 7.12), but the seasonal variability was, again, not investigated. In the EPO, the few whale associated sets precluded pattern identification, but whales' sightings varied from i) the coastal area of Peru (seasons 1 and 2), ii) east of the Galapagos Island (year-round), 7.13). These areas correspond to higher chlorophyll-a concentration, especially during the periods mentioned (Appendix 7.A.1).

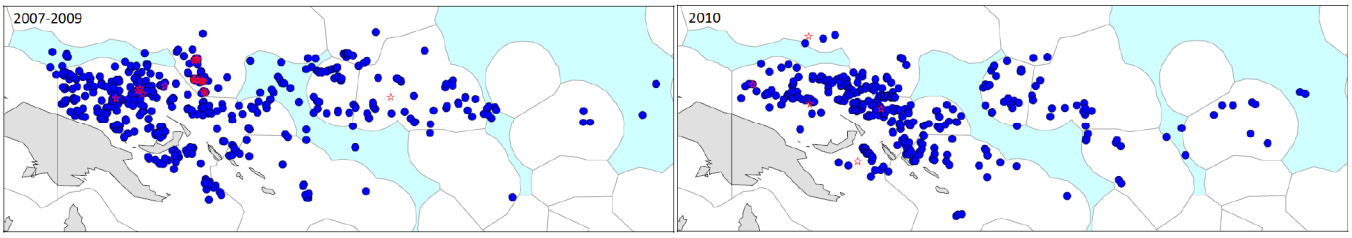


Figure 7.12 Whale associated sets (blue circles) and interactions (red star) recorded by observers in WCPFC 2010).

To sum-up, it appears that the proportions of whale and whale shark associated sets in the WCPO are similar to the ones found in the EAO and WIO. Mortality rates were also higher in the WCPO for both megafauna groups, which underline the need to investigate apparent and post-encirclement (underway for whale shark) survival rates as well as to promote safe release methods. In the tropical fishing grounds, areas of whale and whale shark associated sets correspond to main fishing areas, presumably with little temporal variability. In the northern part of the WCPO, where fishing effort has increased in recent years, whale shark sets were historically higher than in tropical waters during the upwelling period along the Japanese coast. In contrast in the EPO while few whale and whale shark associated sets were recorded, spatio-temporal variations in the main areas of co-occurrence and interactions between these megafauna species and the purse-seine fishery was detected. Similarly to the results found in this thesis, the co-occurrence with the purse-seine fishery appears to be linked to productive environments (chlorophyll-a concentrations), as well as relatively high SST for whale sharks. Therefore in both the EPO and WCPO spatio-temporal variation in co-occurrence and interactions between whale sharks, baleen whales and the purse-seine fishery should be investigated in more details with link to environmental variables.

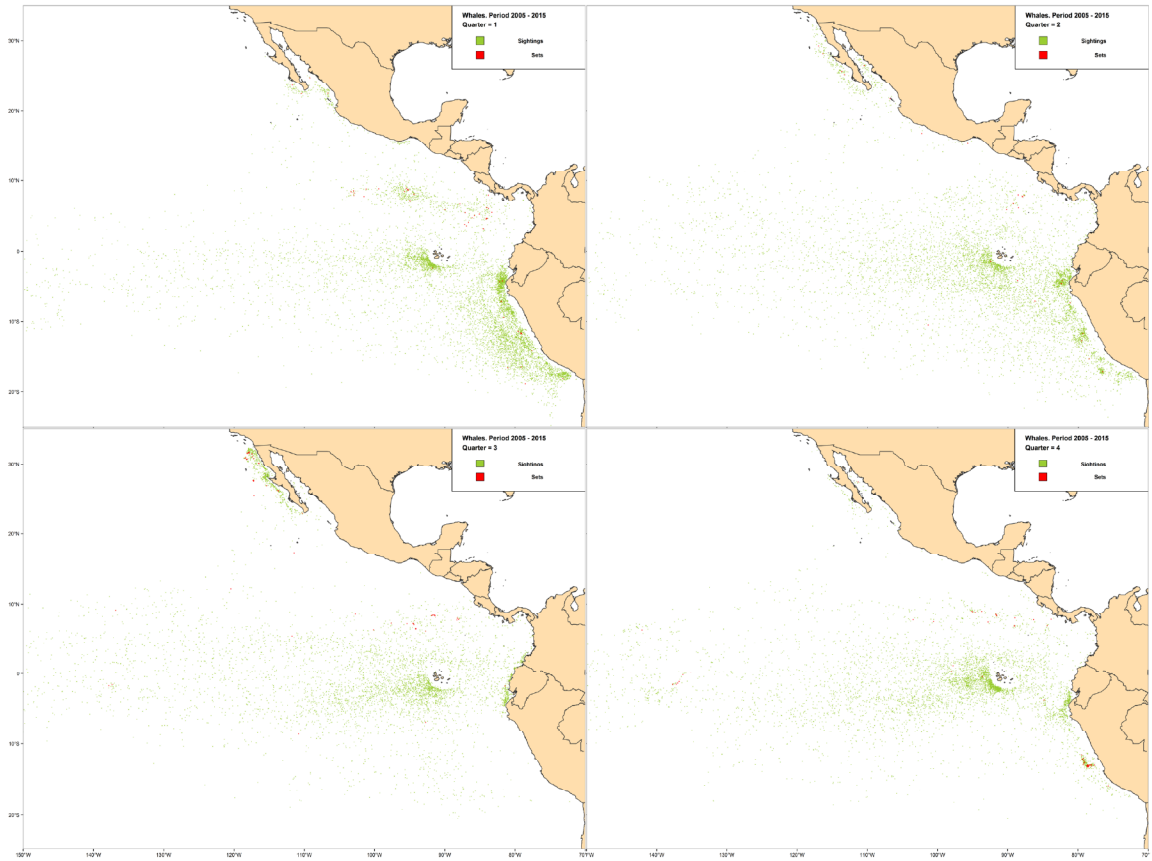


Figure 7.13 Spatio-temporal distribution of whale associated sets and sightings recorded by scientific observers per season (four quarters) in the eastern Pacific Ocean over the 2005–2015 period (Marlon Roman (IATTC), personal communication).

7.2.2 Catch and bycatch diversity on megafauna associated sets

Apart for dolphin sets, no studies have investigated the catch and bycatch species captured in megafauna associated sets in the EPO and WCPO. Worldwide tuna species Hall *et al.* 1999 Hallier and Parajua 1999). However, for sets associated to megafauna species in the WCPO and EPO, only data for dolphin sets in the EPO are available, showing the IATTC 2010). Skipjack tunas 7.14) are of similar length (50–55 cm) than in 5.2). For yellowfin tuna, however, the main peak in individuals captured on free school and whale associated sets in the EAO and WIO were slightly higher (150 cm) than individuals captured on dolphin sets in the 7.14). In addition, it also appears that the bycatch found in dolphin sets is also different than in whale (or whale shark) associated sets, with generally smaller bycatch rates Hall *et al.* 1999). While no more details can be formulated with

the available data, a more detailed comparison of dolphin and baleen whale sets could be Lezama-Ochoa 2016) have investigated bycatch diversity (e.g. species richness, Shannon diversity and Pielou's evenness) in FAD and free school sets between EAO, WIO and EPO. However, as the three oceans were studied separately, inter-ocean comparison of the diversity indices could not be performed. Similarly, a comparison with our study is not possible as different diversity indices and methods were used. The authors however mentioned that bycatch diversity was better assessed in the EPO due to extended sampling (100% observer coverage).

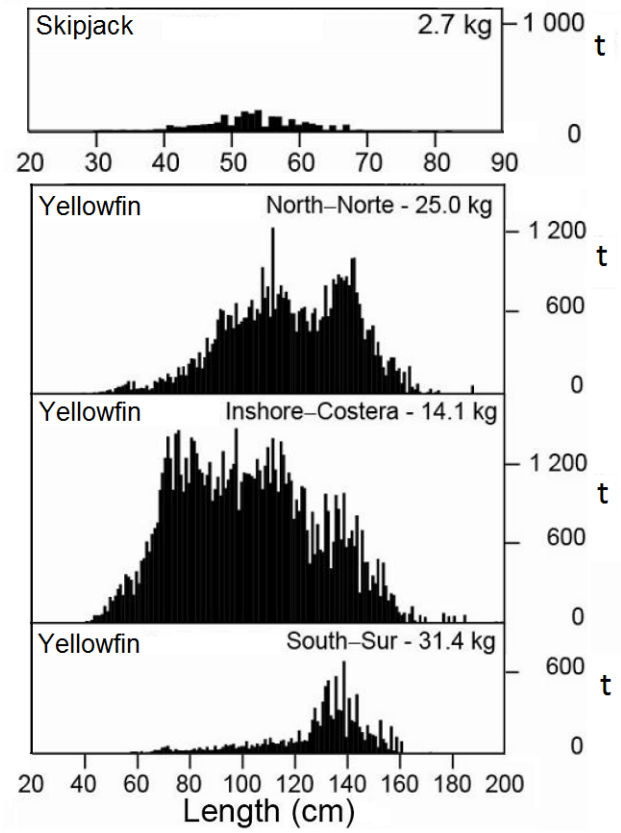


Figure 7.14 Size spectrum of tuna catch on dolphin IATTC 2010).

7.2.3 Fishing effort regulation measures

In both the WCPO and EPO, fishing effort regulation measures have been implemented to protect stocks of tropical tunas. In the WCPO, a FAD moratorium (fishing and any FAD operation) over main fishing areas (20°N–20°S) has been implemented for two months in 2009, then three months in 2010 (July–September) (WCPFC CMM-2008-01 and CMM-2011-01). The main objective was a 30% reduction in fishing mortality on bigeye tuna and a reduction in the risk of overfishing of yellowfin tuna within 3 years. In 2013, as well as the following years, as the objectives were not reached, the measures was extended. Therefore, in 2015

and 2016 vessels have to comply with three-month FAD moratorium (July–September) and i) additional two-month FAD moratorium (January–February) or ii) 30% reduction in the annual number of FAD sets (CMM-2014-01). Finally in 2017, ban of FAD sets in the high sea will be proposed. To our knowledge, the potential side effects of these fishing effort regulation measures have not been investigated. Concerning megafauna associated fishing sets, an increase in the number of whale and whale shark associated fishing sets may be expected. This may be particularly important for whale shark associated sets in the northern area of the WCPFC. Indeed in recent year fishing effort has expended to area above 20°N (5–11% of the Clarke 2015) and historical Japanese purse-seine fishery completed twice more Matsunaga *et al.* 2003). In addition, whale shark associated sets may remain under-reported, as the 100% observer coverage only apply to the 20°S–20°N area. Nonetheless, potential fishing effort relocation on megafauna associated fishing sets could also be investigated in this ocean using Monte Carlo simulations (Chapter 6).

In the EPO, concerns about increasing catch of juvenile bigeye tuna on FAD also led to the implementation of fishing effort regulation measures. Therefore, since 2004 vessels have to respect 40 days fishery closure every year (1st August to 11th September or 20th November to 31st of December) (IATTC resolution C-04-09). This led to a reduction in the number of days spent by vessel at port the rest of the year, but also an increase in the number Torres-Irineo *et al.* 2016). Effects on other megafauna associated fishing sets (whale and whale shark) have not been investigated, as they are considered to be relatively low. Intentional whale shark associated fishing sets is prohibited (since July 2014) and full observer coverage exists in this ocean. It is therefore unlikely that this fishing mode would highly increase nowadays. However effects on the number of whale shark associated sets performed per year (mostly made from January to March) after the first implementation of the closure in 2002 (one month closure in December) and its modification in 2004 could be investigated using BA analysis (see Chapter 6).

7.3 Key strengths and limitations

7.3.1 Main contributions

The main contributions of this thesis have been to increase the knowledge on megafauna/ purse-seine fishery interactions, which may be used by tRMFO to define conservation and management measures in the frame of the EAF. Overall our findings showed that bycatch and encircled megafauna, especially of sensitive species or populations, should be accounted

for when implementing management measures. In order to do so, detailed knowledge on the biology and ecology of the species involved is primordial. Long-term open-ocean fishery data allowed us to deepen our knowledge of relatively rare species (whale shark, baleen whales). In addition, details information on their interaction with the purse-seine fishery, included impact on their populations, has been gathered. Finally, simulations of management and conservation measures allow investigation of potential side effects following their implementation. We acknowledge that fisher-at-sea behavior is very difficult to predict, especially following fishing effort regulation measures. Nevertheless similar approach should be investigated before the implementation of any regulation. It is particularly important in an EAF, where other species than the targeted ones should be accounted for, as well as species interactions (i.e. trophic) and habitat.

In addition, this thesis brought new information on relatively rare species. For instance, whale shark biology and ecology is still poorly known, and most available information has been collected from costal aggregations. Studies dedicated to whale shark oceanic ecology have been also based on purse-seine fishery data and have previously describe Sequeira *et al.* 2013a 2014). Similarly, cetaceans distribution were also known to be influenced by Forney 2000 Monsarrat *et al.* 2015). This thesis reinforces previous knowledge showing that the co-occurrence of whale sharks, baleen whales and the purse-seine fishery (i.e. the association with tuna schools) is also mostly influenced by productive environments. In addition the association between whale shark, baleen whales and other pelagic species (i.e. tuna, sharks, billfishes) has been investigated. Finally new whale shark ecological data, such as possible calving areas and female movement in the EAO, has been identified.

This thesis also permitted to define the catch and bycatch composition on whale and whale shark associated sets. This therefore refined previous knowledge, especially on whale shark sets, which were considered as FAD sets, while our study showed a more intermediate status between FAD and free school sets. This could be of importance in tuna management and fishing statistics at it showed that whale shark sets could need a specific set category, while whale sets could still be combined with free school sets. In the current atmosphere of the tuna fishery looking for labels and good perception from the public, the separate classification of whale, but especially whale shark associated sets could therefore be pursued. Indeed, while NGO pressure against FAD is increasing, fishing companies are currently looking for traceability of the tuna captured in order to valorize tuna from free school or megafauna associated sets. Therefore it may be particularly interesting to separately classified whale shark sets, especially considering the lower bycatch rates on

this fishing mode than on FAD, which appears as the main argument of NGOs anti-FAD campaigns.

7.3.2 Limitations

Within each chapter, some inherent limitations derived from the type of data used or the analyses performed have been discussed, they will not be repeated here. General limitations that could improve results presented and that have oriented our global choices of analysis or of data used, and that should be considered in similar work are however mentioned below.

Firstly, some limitations concern the type of data used. Scientific observers data have the main objectives of assessment and monitoring bycatch taken by tuna purse-seiners. In the EAO and WIO, the period covered by this database is smaller (continuous data collection programs since 2003) than fishery logbooks (since 1980). In addition, before 2014, the observer coverage was of ∼10%, which is considered to be too low in order to correctly assess bycatch rates even for relatively abundant bycatch species (i.e. >20% for billfishes, sharks Lennert-Cody 2001). Therefore, it is unlikely to be sufficient to assess relatively rare megafauna species interacting with the purse-seine fishery. Hence, in view of the lack of full scientific observer coverage in most of the data used in this thesis, it cannot be excluded i) the underestimation of whales and whale shark interactions with the purse-seine fishery, ii) similarly, also the underestimation of apparent mortality rates of both megafauna species, and iii) a possible "observer effect" (i.e. skipper modifying their fishing practices when observer are onboard). In addition, in scientific observer, as well as logbook data, the baleen whale species were mostly not identified. Considering the difference in biology and ecology, as well as possibly the difference in the impact of the purse-seine fishery on each of the four baleen whale species interacting with the purse-seine fishery in the EAO and WIO, it would have been relevant to have more detailed information per species. Additionally, logbook data used in this thesis corresponds to the raw data declared by captains, without any corrections in term of tuna species and commercial category. Indeed, it is known that some species are frequently misidentified (especially juveniles yellowfin and bigeye tunas) and are subject to statistical corrections based on field sampling. While this is of particular importance for stock assessment, we do not consider that it would highly influence results of this thesis (Chapters 5 and 6) as most yellowfin and bigeye tuna catch in megafauna associated sets are large individuals (i.e. well identified). Furthermore it was not possible to use the corrected data, as data were smoothed by large area and season with only two fishing mode: FAD (including whale shark set) and free school (including whale set) sets available.

However, the sub-regions ("ET zones") used for spatial sampling and establishing corrected species compositions and length structure in both the EAO and WIO were also used in this thesis (Chapter 6). In addition, for the sake of simplicity, the same sub-regions were used for bycatch (i.e. in Before-After (BA) analysis and simulations). However it is likely that other spatio-temporal subdivisions would have been more accurate for encircled megafauna and bycatch species distribution.

Secondly, some limitations in the methods implemented can be considered. In the simulations (Chapter 6), it should be mentioned that when simulated the ban of whale shark associated sets, we assumed that this fishing mode could be avoided. Yet, we have found that most whale shark sets are incidental. This should therefore be kept in mind, and reinforces the need for full observer coverage, as we may expect under-reporting of whale shark sets by skippers when these are banned. In addition, the main limitations of the simulations are the fact that there is no match between areas and periods of high FAD fishing and of high megafauna associated fishing sets. Therefore time-area regulations are unlikely to affect one another. What would be more relevant to investigate, but really hard to simulate, would be to predict the effect of one regulation during a specific season on other fishing seasons. For instance, during the season of the FAD moratorium the tuna catch would decrease, which may lead to change in fishing strategies and distribution also during other seasons (i.e. more FAD sets or inversely more sets on other fishing modes) to compensate tuna catch loss. In the bycacth biodiversity analysis (Chapter 5), it can be argued that too few megafauna associated sets (especially whale shark sets in the WIO, i.e. 24 sets) limited the analysis. It is however unlikely that the number of whale shark associated sets will highly increase in the WIO in the future as i) the number of whale shark sets is lower in this ocean than in the EAO and ii) intentional setting on whale shark is now forbidden.

7.4 Perspectives

First of all, it is clear there is a need for detailed knowledge on the biology and ecology, as well as abundance estimations and trends, for whale shark and baleen whales populations present in the purse-seine fishing grounds. In this thesis, quantitative studies of whale shark and cetaceans co-occurrence and interactions with the European purse-seine fishery, as well as estimation of apparent impact on the populations involved, have been performed. Considering the recent increase in the scientific observer coverage in both the EAO and WIO, such studies, especially in terms of apparent survival rates following interactions with the fishery, should be continued in the future. In addition, other purse-seine fishing fleets (e.g. Ghanaian and Seychelles) are also operating in the EAO and WIO should

also be included in such studies to fully assess the spatio-temporal interactions between these megafauna species and the purse-seine fishery at the scale of these oceanic basins. In addition, safe release methods for encircled, as well as vulnerable bycatch megafauna species, should be promoted for these other fishing fleets as well.

Secondly, many aspects on the megafauna interactions with the tuna purse-seine fishery in the WCPO and EPO are still lacking. It could be very useful to expand the different analysis performed in this thesis to these oceans. Indeed, the spatio-temporal co-occurrence and interactions between the purse-seine fishery and whale shark and baleen whales could be investigated in terms of Sightings (of Capture) per Unit of Effort in the WCPO and EPO. Moreover, possible link with environmental variables should be explored as it appeared that the co-occurrence is linked to productive environments in these oceans as well. Furthermore, the targeted species and size composition and diversity in bycatch species captured in association with whales and whale sharks could be studied in both oceans, with a specific comparison with dolphin sets in the EPO. In this way, it could allow for a general comparison of all these aspects among ocean basins. In the WCPO, mortality rates have been found to be higher than in the EAO and WIO. Whale shark tagging experiment has started in this ocean as well, in order to assess post-release survival rates (to date no successful tagging has occurred). Likewise, the tagging of additional individuals should also be pursued worldwide. This should include several whale shark sizes, including juveniles potentially more sensitive to encirclement, as well as individuals release using various methods (e.g. safe release, towed by the skiff). This would therefore allow for estimation of post-capture survival rates, as well as movements outside fishing area. Moreover, fishing effort regulation measures have also been implemented in both the EAO and WCPO. Therefore, side effects of these measures on the tuna catch, bycatch, as well as megafauna associated fishing sets could be investigated using Before-After (BA) analysis in case of past or current measures, as well as using Monte Carlo simulation to forecast potential consequences in the future. Similarly, intentional whale and whale shark associated fishing sets are now prohibited in most oceans (except the EAO and the EPO for whale associated sets) and full observer coverage is reached or pursued. Hence, rates of encirclements prior and after these measures, as well as consequences of fishing effort and strategies could be explored.

Thirdly, safe release methods for whale sharks (and whales species when appropriate) should be encouraged in all oceans. Similarly, for megafauna bycatch species, mitigation measures when encircled in the net and good practices when brought onboard are also very important to limit the impact of the fishery on these species. In parallel, studies should be implemented for sensitive megafauna species still poorly documented. It is for instance the case for manta and mobula rays, hammerhead sharks and some sea turtles (i.e. leatherback,

hawksbill and Kemps turtles). For these species with relatively high apparent survival rates (sea turtles, manta and mobula rays), longer term post-release survival rates should also be investigated (electronic tagging experiment) in order to adequately assess the impact of the fishery. This could also come along increasing knowledge on the biology and ecology of these pelagic species, as identification of key areas (mating, calving, nesting or nursing areas) may be particularly important for conservation. Hence, information on key reproductive and main bycatch areas could be potentially used to design fishery closures to limit the impact of the fishery on sensitive megafauna species. Likewise, simple information could be recorded by observers in order to better estimate apparent survival rates. For instance, the use of similar code for condition upon release of sensitive species than in the WCPO, along with individuals fate could improve the data currently collected.

Additionally, purse-seiners could support scientific research for complementary aspects. While we acknowledge that scientific observers already have to collect and record high amount of data, the large areas covered by purse-seiners and the variety of pelagic species encountered could allow for increasing knowledge of rare species. Thus, genetic samples could be relatively easily collected. This would be particularly relevant for whale shark as the EAO population has not been included in previous genetic studies. In addition, it could help confirm species identification (e.g. Kemp's turtle) and therefore possibly help define distribution range. Similarly, conventional tagging of whale sharks and baleen whales could also be relatively easy when encircled in the sack. Animals encircled several times during the same fishing season, as well as sightings in other areas could be identified. Possible photographic identification of encircled whale sharks has also been investigated (see general appendices) in order to compare with existing photo-ID database (Arzoumanian et al. 2005). However it has been proven difficult, due to the movement of the shark and the vessel, to have correct pictures of the area along the gill. Finally, for cetaceans, and especially baleen whales, a better knowledge of species present in fishing areas and interacting with the purse-seine fishery could be possible by at-sea observation protocol (see general appendices). This has started to be implemented by scientific onboard observers, but species identification remains difficult when species are not directly interacting with the vessel (i.e. relatively close).

Finally, current FAD management measures focus on limitation in the number of FAD deployed. However, the limitation in the number of FAD sets completed per vessel could also be investigated, and has already been examined in the WCPO. Therefore it could be interesting to simulate a limit in the number of FAD sets completed by vessel per year. This could possibly have unexpected results in term on fishing effort relocation. For instance, vessels might concentrate the number of FAD sets during FAD fishing periods and areas. In

contrast, during the other seasons, fishing effort may likely be highly relocated toward free school and megafauna associated sets. Overall, to limit possible under-reporting of these sets by skippers, full observer coverage is needed in the future in all oceans and fishing fleets.

7.5 Conclusion

This thesis underlined that most megafauna associated sets in the EAO and WIO involve whale sharks and baleen whales. The co-occurrence between these two megafauna species and the tropical tuna purse-seine fishery occur in specific seasons and areas and are mostly linked to highly productive environments. The associations of whale sharks and baleen whales with other pelagic species have been investigated. Large tunas, sailfishes and sharks were mostly found in association with baleen whales. On the other hand, small tunas (skipjack and juveniles bigeye and yellowfin), but also large ones, marlins, sharks and pilotfishes were found in association with whale sharks. Finally, time-area fishing effort regulations on FADs or megafauna conservation measures were found to have little effect on one another.

The identification of main interactions and bycatch areas, as well as main bycatch diversity hotspots are relevant issues for species and ecosystem conservation. However other indices of biodiversity (taxonomic and functional), as well as species (or populations) vulnerability and knowledge on their biology and key habitats (mating/calving) are also important aspects. It is therefore primordial to have good biological and ecological information on megafauna species. Hence, when possible, all of these information should be accounted for by tRFMO when implementing conservation measures.

Some solutions have been proposed to reduce and mitigate bycatch, especially for vulnerable species, as well as to avoid the overexploitation of tuna stocks. Hence it makes sense to consider that due the complexity of the challenge there is no unique solution. FAD fishing should be regulated and its ecological impact should be limited (habitat, tuna ecological trap, ghost fishing...). Likewise, impacts on bycatch and megafauna species should also be accounted for. This may be done by combining time-area closure or mitigation measures, as well as good practices to release species encircled or landed onboard. Finally, before the implementation of any regulation, a global reflection at the scale of the fishery in an EAF management should be carried out with investigation of potential side effects.

Appendix 7.A

Chlorophyll-a concentration and Sea Surface Temperature in the tropical Pacific Ocean

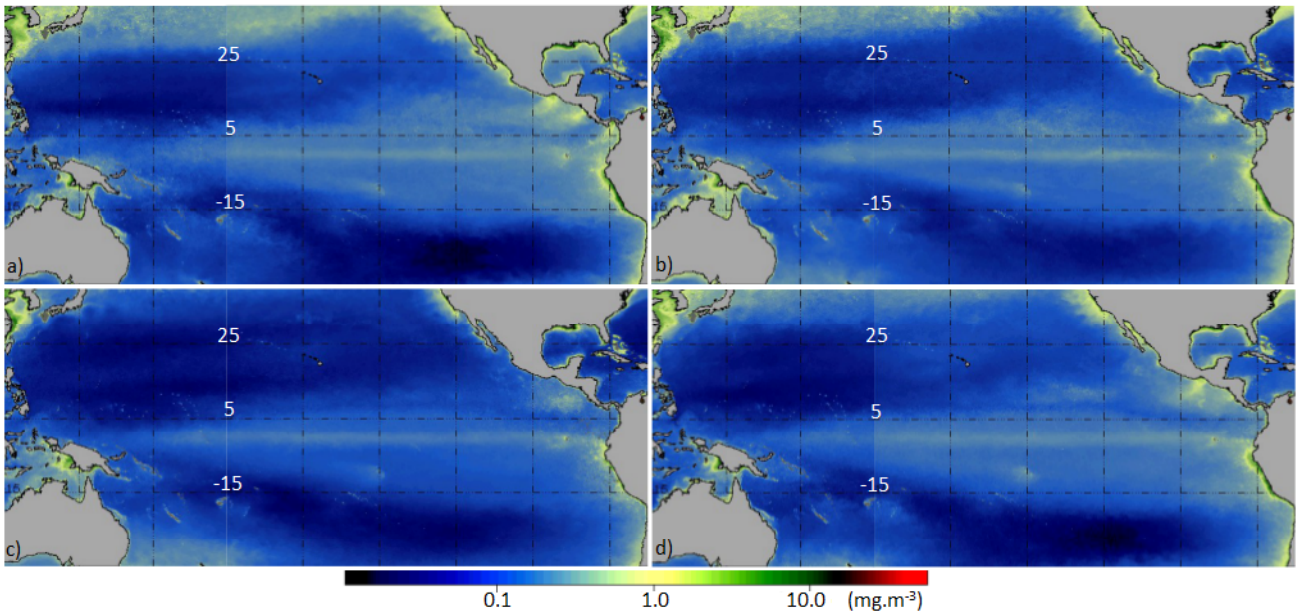


Figure 7.A.1 Chlorophyll-a concentration (mg.m^{-3}) seasonal variability (by quarter) in the Pacific Ocean in the 2007–2010 period (source MODIS, Liliana Pascuali personal communication).

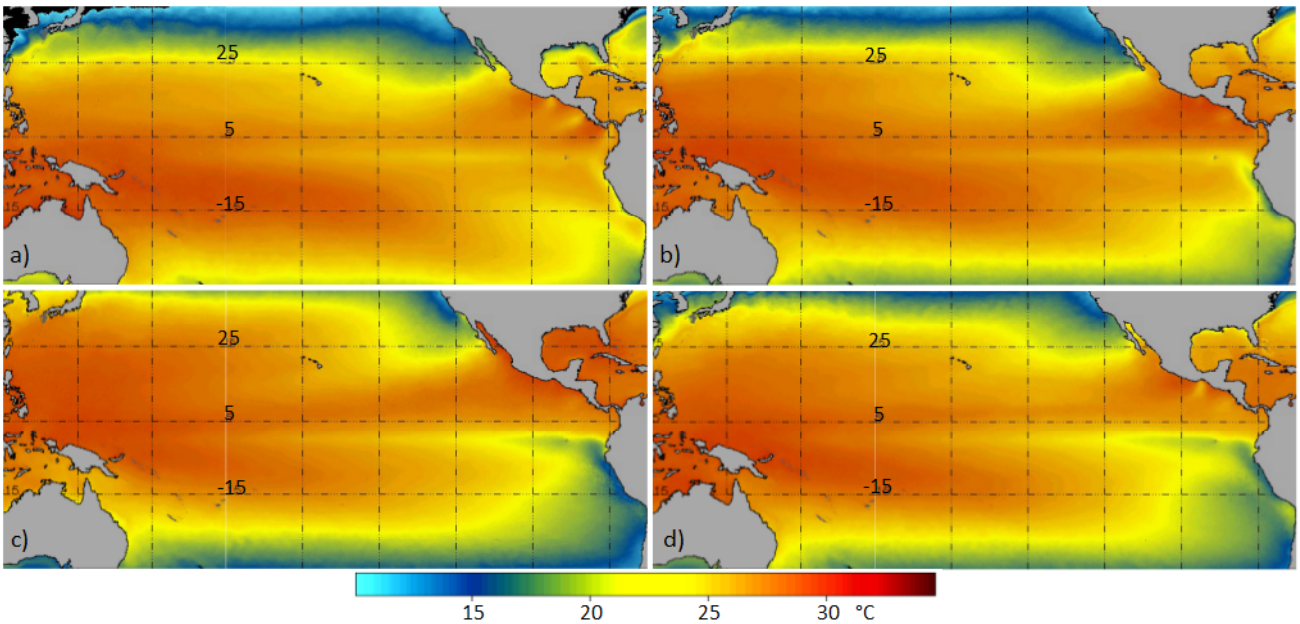


Figure 7.A.2 Sea Surface Temperature (SST; °C) seasonal variability (by quarter) in the Pacific Ocean in the 2007–2010 period (source MODIS, Liliana Pascuali personal communication).

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Appendices

Version 2 – Janvier 2015

Opération Marquage de Requins Baleine[1]

L'objectif de cette opération est de quantifier la survie de requins baleine sur le long terme, après encerclement et libération d'une seine.

Le marquage est réalisé avec des marques appelées « Pop-Up Satellite Archival Tags », qui gardent en mémoire les données enregistrées, puis les transmettent lorsque la marque se détache automatiquement de l'animal après une période définie (6 mois dans notre cas). Une fois à la surface de l'océan, les données recueillies sont transmises au système satellite Argos. Ces marques enregistrent les déplacements de l'animal, la profondeur et la température de l'eau.

Les marques transmises aux observateurs sont pré-programmées et déjà allumées, l'observateur n'a aucune manipulation à faire avant le marquage.

Les conditions pour réaliser le marquage:

1) Au début de la marée, l'observateur doit **s'informer auprès du capitaine** pour savoir s'il est au courant de l'opération de marquage de requins baleine. **Lui décrire en détail la procédure** que vous souhaité réaliser, et ce qu'il devra faire en cas de capture d'un requin baleine (attendre la fin du coulissage, puis si le requin est bien placé et que le marquage est possible, effectuer le marquage avant le début des manœuvres de libération).

   Sans l'accord préalable du capitaine, aucune opération de marquage n'est envisagée, le déroulement de **la procédure doit être expliquée et discutée avant**.

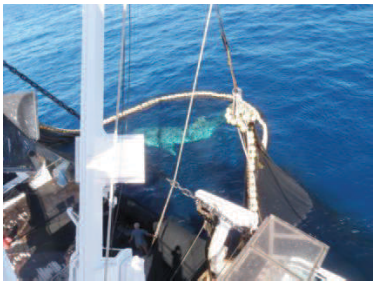
2) Si un requin baleine est encerclé, attendre **la fin du coulissage**, lorsque la poche est formée ; juste avant le début des manœuvres de libération.

3) **La mer doit être calme.**

4) **Le requin doit être bien placé dans la poche, le long du bateau, avec le dos visible en surface.**

[1] Source : Lauriane ESCALLE (lauriane.escalle@ird.fr)

Ci-dessous les différentes étapes avant un éventuel marquage :



Un requin baleine est observé dans la senne.

La mer est calme.

Préparer le matériel pour le marquage (fixer la marque sur la « lance » de marquage).

Lorsque l'équipage se prépare à effectuer les manœuvres de libération (en général une fois la plupart des thons ont été remontés à bord), les avertir de votre opération de marquage.

Si le requin est bien placé dans la poche, le dos visible en surface. Se placer sur le pont, au dessus du requin baleine.

Dans la poche, le requin bouge, et peux se retourner sur lui-même, ne rien tenter si le requin est sur le dos (face ventrale visible) ou sur le côté. Attendre que le dos de l'animal soit en surface, la base de la nageoire dorsale doit être visible et facilement accessible.

Cas idéal, le requin est bien placé dans la poche et la base de nageoire dorsale est bien visible.

2

Le matériel utilisé :

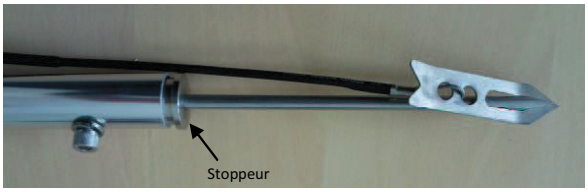
1) La marque « pop-up » est fournie directement accrochée à une « ancre » en titanium, qui est la partie venant se placer dans le muscle du requin baleine.

2) Le marquage va s'effectuer à l'aide d'une perche de 4m de long.

3) La perche est équipée d'un applicateur (à monter au préalable à l'aide d'une vis), sur lequel on vient fixer l'ancre (et donc la marque). La marque doit être tenu sur la perche à l'aide d'un élastique (pas trop serré pour facilité son détachement lorsque la perche est retirée, une fois la marque en place).

Montage de la marque sur l'applicateur et la perche :

Zoom de l'extrémité de la perche, avec l'ancre fixée au bout de l'applicateur :



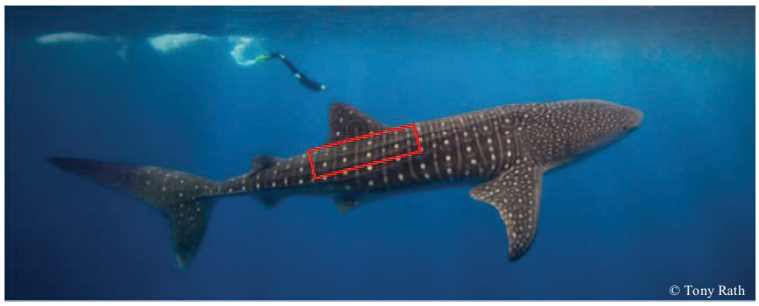
4) Pour éviter de perdre la marque, elle peut être attachée à l'aide de fil nilon.

3

La procédure de marquage :

1) Se **positionner sur le pont, au dessus du requin baleine,** au niveau de la nageoire dorsale. La marque est fixée sur l'applicateur au bout de la perche, se rapprocher au plus près du requin baleine, et attendre le meilleur moment (le bateau et le requin bougent).

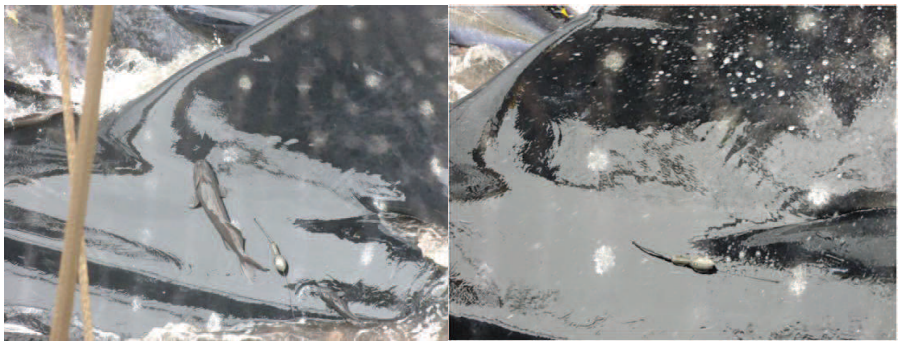
2) **La marque doit être placée à la base de la nageoire dorsale** (cf zone rouge ci-dessous), dans le muscle du requin baleine. Le « stoppeur » au bout de l'applicateur permet de ne pas l'enfoncer trop profondément.



3) **Il faut planter la perche d'une seule fois avec beaucoup de force**, l'applicateur va s'arrêter au niveau du stoppeur. Ne pas hésiter, car la peau du requin baleine est très épaisse et dure.

   Vous pouvez éventuellement demander à un membre de l'équipage de réaliser le marquage, en lui expliquant bien la procédure et l'emplacement à viser.

4) Tout l'applicateur doit être entré dans le muscle du requin, jusqu'au « stoppeur ».



4

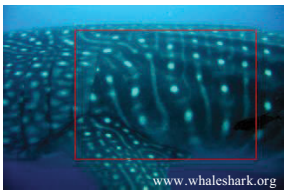
5) **Si le marquage échoue**, remonter la marque à bord. Lorsqu'elle à été mouillée, la marque commence à enregistrer des données. Il faut donc **obligatoirement la désactiver** en passant un aimant le long de la zone métallisée, comme expliqué ci-après.

   La marque peut ensuite être réutilisée ultérieurement pour un autre marquage.

6) **Estimer la taille** de l'individu marqué. Pour cela se placer dans le nid de pie et prendre des repères visuels sur le pont. La distance entre 2 points repérés sur le pont sera ensuite mesurée après le coup de pêche.

   Si le partie ventrale a été visible, noter également **le sexe** (présence ou absence de clapser).

7) Après le marquage, si les fentes branchiales sont visibles, et que cela est possible, prendre une photo de la zone située à l'arrière des fentes branchiales.

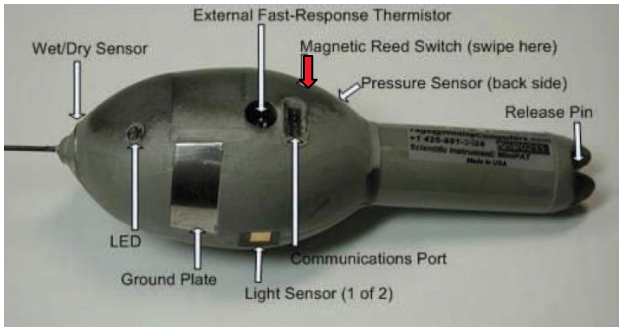


Demander à être filmé pendant l'opération de marquage (ou filmer la personne réalisant le marquage).
Prendre une **photo de la marque en place**.

Différents paramètres doivent être noté :

- Le temps passé par le requin dans la senne
- Et le **temps passé par le requin dans la poche**
- Le **temps pris par la manœuvre de libération**
- Le requin a-t'il été libéré avant ou après salabardage ?
- La **méthode de libération du requin baleine** (description et vidéo si possible)
- L'état général du requin baleine lors de sa libération (notamment blessures éventuelles, signes de faiblesse...)
- Décrire tout problème rencontré pendant le marquage

Désactivation de la marque



Pour connaitre le mode où se trouve la marque (en enregistrement ou en standby), il faut passer un aimant le long de la zone désignée par une flèche rouge sur le dessin ci-dessus (Magnetic Reed Switch). La LED va émettre un clignotement différent selon l'état de la marque :

- En standby : 2 clignotements courts, pause, 2 clignotements courts, pause, 2 clignotements courts, pause, 1 long clignotement
- En enregistrement : 10 clignotements courts puis 1 long clignotement.

Si la marque à été mouillée et qu'elle est en mode "enregitrement", **il faut absolument la désactiver**, donc la faire passer en mode Stanby. La procédure est la suivante :

Passer un aimant sur la zone magnétique. La marque émet le clignotement désignant le mode « enregistrement »: 10 clignotements courts, puis 1 long. Passer à nouveau l'aimant sur la zone magnétique pendant ce long clignotement.

Vérifier l'état de la marque ensuite, en testant de nouveau le mode (voir plus haut).

Une fois un individu marqué, veuillez communiquer à :

lauriane.escalle@ird.fr

Le numéro de la marque
La date et l'heure
Les coordonnées GPS correspondant au marquage
La taille et le sexe (M, F ou Ind.) de l'individu marqué
Les différents **paramètres et observations demandés**

Version 2.2 – Janvier 2016

Protocole d'observation des mammifères marins[1]

A destination des observateurs embarqué à bord des thoniers senneurs tropicaux

Le but de ce protocole est de collecter des informations sur les interactions entre les mammifères marins et la pêche thonière à la senne dans les océans Atlantique et Indien. Ainsi l'objectif est d'identifier des zones et périodes présentant de nombreuses interactions et de pouvoir faire le lien éventuel entre ces zones et des conditions environnementales particulières.

Le but est de renforcer les données déjà collectées par les observateurs à bord des thoniers, et ainsi d'obtenir des informations précises sur les espèces rencontrées et encerclées, de pouvoir estimer leur abondance dans les zones de pêche et donc mieux caractériser l'interaction des espèces de mammifères marins avec la pêcherie thonière à la senne.

Les observateurs embarqués enregistreront leur effort d'observation ainsi que les observations de cétacés en mer i) lorsque les navires feront route vers les zones de pêche ou ii) lors des prospections sur les zones de pêche et iii) lorsque les conditions d'observations seront favorables.

Ce protocole décrit la méthode applicable sur une plateforme d'observation simple (une seule plateforme avec 1 seul observateur). Ainsi les observations n'aurons que peu de valeur si l'effort d'observation, ainsi que les conditions (état de la mer, conditions générales pour la détection) et tous changements au cours des observations, ne sont pas relevés avec la plus grande rigueur.

Période et durée d'observation

L'observation des mammifères marins peut se faire à n'importe quel moment de la journée si les conditions d'observations sont bonnes, mais vous devez vous concentrer uniquement sur cette tâche pendant cette période (appelée session d'observation). Cependant ce travail vient en complément (mais pas en priorité) des autres tâches d'observateur, il ne doit donc pas vous distraire des autres activités demandées.

Vous ciblerez une session d'observation de 30 mn par jour si les conditions d'observation sont satisfaisantes. Mais plusieurs sessions peuvent être effectuées la même journée si vous avez le temps.

Une session d'observation est divisé en « leg ». Un leg est un segment de route linéaire pour lequel il y a eu effort d'observation. A chaque changement de direction ou d'activité du navire, il faut créer un nouveau leg. Une session d'observation peux être composée d'un seul leg de 30 minutes. Cependant si le navire change de direction, si vous devez remplir le formulaire A ou faire n'importe quelle autre tache, il faut arrêter le leg en cours et en commencer un nouveau. Ainsi une session d'observation peux également être composée de plusieurs legs. Pour maintenir une durée d'observation homogène, la somme des différents leg dans une session d'observation doit faire 30 minutes, avec un écart entre les différents leg ne dépassant pas quelques minutes (la durée totale d'une session d'observation en comptant les legs et les écarts entre les legs ne doit pas dépasser 1 heure).

Le seul cas où une session d'observation peux être interrompue avant 30 minutes est lorsque le bateau arrive sur un système détecté et se prépare pour une calée. Le bateau observe le banc en tournant autour, la prospection ne se fait plus en ligne droite et est sur une zone réduite. La session d'observation doit donc s'arrêter.

Une période appropriée pour effectuer une session d'observation est lorsque le bateau fait route (en veille de pêche ou non). Vous pouvez vous poster à la passerelle ou la proue, tout en restant à l'écoute d'éventuels systèmes observés ou changements d'activités afin de remplir, entre les legs, le formulaire A (route) du manuel d'observateurs.

Il est très important de ne pas commencer une session d'observation seulement quand un mammifère marin est observé, mais de décider volontairement quand vous allez commencer. Il se peut donc qu'il y ait des legs sans observation (le cas contraire donnerait des résultats biaisés). Le choix des sessions d'observation doit donc se faire de manière aléatoire quand vous disposez d'environ 30 minutes de libre et que les conditions d'observation sont bonnes.

Si une observation est faite hors d'une session d'observation, ne pas commencer un leg, mais seulement noter l'observation dans la colonne « système observé » du formulaire A (route) du manuel d'observateurs. Avec les détails correspondants (espèce ou groupe de cétacés / nombre individus) dans la colonne note.

Exemples : POD_20 (photo 35)/MYS_1 (photos 36-40). Pour 20 petits odontocètes, photo 35 et 1 mysticète, photos 36 à 40

DST_≈50 (photos 41-50). Pour une cinquantaine de dauphins bleu et blanc (photos 41 à 50)

Conditions d'observation

Sachez que la vitesse idéale pour observer doit être comprise entre 8 et 12 nds, en deçà il y a risque de doubles comptages et au-delà de ne pas détecter les animaux.

Pour chaque leg, vous décrirez l'état de la mer exprimé en indice de Beaufort (annexe 3, tableau 4 du manuel), la nébulosité (couverture nuageuse en octa, tableau E1 ci-dessous), ainsi que les conditions générales d'observations : bonne, moyenne ou mauvaise. Si vous jugez que les conditions sont trop mauvaises, stoppez l'observation.

Les conditions d'observation sont certes subjectives, mais dépendent néanmoins d'un certain nombre de paramètres qui affectent plus ou moins la détection des cétacés ; comme la luminosité (éblouissement), la nébulosité, l'humidité (pluie, brume), la couleur de la mer (bleue, grise, etc.). Par exemple, vous pouvez observer avec de bonnes conditions météorologiques (mer < à 2 Beaufort, ciel dégagé) mais estimer que la détectabilité est moyenne voir mauvaise car l'éblouissement par le soleil occasionne une gêne trop importante.

Tableau E1 : La nébulosité correspond à la fraction du ciel occupée par des nuages, mesurée en octa (1/8 de ciel)

Code	Description
0	Ciel complètement dégagé
1	Ciel peu nuageux
2	Quart du ciel ennuagé
3	Entre le quart et la moitié du ciel ennuagé
4	Moitié du ciel ennuagé
5	Plus de la moitié du ciel ennuagé
6	Ciel très nuageux
7	Ciel très nuageux avec très peu de ciel bleu
8	Ciel entièrement couvert

Méthode d'observation

Vous vous posterez à l'avant de la passerelle ou à la proue, à l'endroit où la visibilité vous semblera la meilleure pour observer les 180° en avant du navire, sans vous mettre en danger (présence de rambardes sur le pont et hors du champ des émissions radars).

Vous n'observez que lorsque les conditions de mer et de visibilité seront bonnes, la détection des petits cétacés en mer étant difficile voir impossible à partir d'un navire de pêche si les conditions de mer sont supérieures ou égales à 4 Beaufort (pour l'échelle de Beaufort reporté vous au tableau 4/annexe 3du manuel observateurs).

On parle de détection visuelle, donc avec les yeux, l'utilisation de jumelles peut éventuellement venir en complément pour confirmer une observation et déterminer une espèce, un nombre, etc. Il faut impérativement écarter toute prospection avec les jumelles, car le champ d'observation en est trop réduit (exemple avec des jumelles 7x50 : champs de vision de 120 m à 1000 m).

Si vous entendez les observations faites par les membres d'équipage aux jumelles lorsque vous êtes en session d'observation, celles-ci sont également répertoriées, en cochant la case 2 « Observation de l'équipage aux jumelles » sur le formulaire E2. Dans ce cas, il faut bien noter la distance à laquelle les mammifères marins ont été observés et leur position par rapport au navire. Cependant, si vous voyez également un groupe de mammifères marins (dans sa bande de 1000 m), précédemment indiqué par un membre d'équipage, il faut également noter votre observation, en précisant bien qu'il s'agit de la même observation que celle précédemment faite par l'équipage.

Précisez en commentaires ou en notes, si pendant une session (ou toutes les sessions de la marée) d'observation, vous n'entendez pas les observations faites par les membres d'équipages aux jumelles, ou si le bateau est en transit (sans veille aux jumelles).

Si l'observateur est posté à 5 mètres de la surface de l'eau, avec des bonnes conditions d'observation (≤ à 2 Beaufort, bonne visibilité et luminosité) il peut détecter des petits cétacés jusqu'à 1 000 mètres voir plus en fonction des espèces, de la taille des groupes et de leur activité. Il est conseillé de ne pas concentrer son effort au-delà de 1 000 mètres afin d'optimiser la détection des cétacés dans ce champs.

Vous devez donc apprendre à vous imaginer une bande d'une largeur connue dans laquelle il devra concentrer son effort. La largeur de cette bande va décroitre avec la dégradation de l'état de la mer. Lorsque la mer est parfaitement lisse ou légèrement ridée (0 à 2 Beaufort), vous pouvez alors vous concentrer aussi loin que possible (max 1 000 m). Dès que les « moutons » apparaissent (3 à 4 Beaufort) cette bande sera réduite et l'effort devra se réaliser sur une distance ne dépassant pas les 500 m.
La notion de distance des objets en mer est très difficile à appréhender, alors il est conseillé d'apprendre à l'estimer, par exemple testez vous en quittant le port avec des amers à la côte, des balises, d'autres bateaux, etc. Les distances pouvant être contrôlées avec le radar de bord ou en sollicitant l'expérience du patron ou d'autres membres de l'équipage.

Relevé de l'effort et des conditions d'observation (Formulaire E1)

A chaque fois que vous êtes en session d'observation, vous relevez à l'aide du Formulaire E1 les informations relatives à l'effort d'observation afin de le quantifier dans le temps et dans l'espace.

La numérotation des sessions d'observation commencera à 1 lors de chaque nouvelle marée. Puis chaque leg est numéroté de 1 à n par session d'observation.

Rappel : Afin de garder une durée d'observation homogène, la somme des legs d'une même session d'observation doit faire 30 minutes, avec un écart entre les différents leg ne dépassant pas quelques minutes.

Il faut commencer un nouveau leg à chaque changement de direction (un leg est un segment de route linéaire) ou d'activité du navire. Cependant, si les critères pour la réalisation d'une session d'observation ne sont plus réunit (la prospection ne se fait plus en ligne droite), on stoppera l'observation. Par exemple

lorsque le bateau arrive sur un système détecté et se prépare pour une calée (observation du banc en tournant autour), ou réalise une calée très rapidement. Dans ces cas où la session d'observation s'est s'arrêtée avant les 30 minutes standard, vous devrez préciser sur le formulaire E1 la raison de cet arrêt.

Ainsi pour chaque segment de route (leg) vous noterez:

- le numéro de session auquel il appartient, le numéro de leg dans cette session et la date

- l'heure et la position des points de début et de fin

- l'activité, le cap (en °) et la vitesse du bateau, la température de l'eau, la vitesse du courant ainsi que les conditions d'observation (état de la mer (=Vitesse Vent en échelle beaufort), nébulosité (en octa), condition générales d'observation) au début du leg.

- si un mammifère marins a été observé, noté que le leg à été positif (+), sinon négatif (-).

- si le leg à été interrompu puis repris (sauf cas d'une calée), noter la raison en cochant une des 4 cases (pour une raison autre que celles proposées, veuillez détailler dans les notes).

Relevé des observations (Formulaire E2)

A chaque fois que vous détectez un groupe de mammifère marins pendant un leg, remplissez une ligne du Formulaire E2. Pour les observations dites « opportunistes », réalisées hors session d'observation, vous utiliserez la colonne « système observé » du Formulaire A. L'investissement dans un bon relationnel avec l'équipage ne doit donc pas être sous-estimé pour cette tâche, en particulier avec les équipiers sur le pont ou en passerelle qui peuvent vous signaler leurs observations, notez les observations faites aux jumelles sans oublier de cocher la case correspondante. Ces observations peuvent notamment combler un biais potentiel entre les différents groupes de mammifères marins observés. En effet quand des baleines sont observées, le bateau fait en général route dans leur direction, donc l'observateur va finir par les voir. Par contre quand des dauphins ou des cachalots sont observés, le bateau continu sa route, ces observations sont donc annoncées aux jumelles (en général à plus d'un mille), et dans de nombreux cas, le groupe va rester au loin, donc l'observateur ne les voit pas. Comme indiquer précédemment, si une observation à été annoncée aux jumelles mais que l'observateur fini par la voir, il ne faut noter que l'observation visuelle de l'observateur.

Pour l'identification des espèces, vous vous reportez au guide d'identification (clé simplifiée d'identification) fournie avec ce protocole. Lorsque que vous n'êtes pas certain de l'identification ne pas tenter de donner une information qui peut s'avérer fausse, donner le groupe (mysticètes (ci-possible différencier les Rorquals des Baleines à bosse), petits odontocètes ou grands odontocètes) auquel appartient le/les cétacés observés. Vous relevez aussi la meilleure estimation du nombre d'individu en n'hésitant pas à préciser ce nombre ou à donner une fourchette dans la colonne note. Si vous distinguez la présence de jeunes donnez également une estimation du nombre (facultatif). Vous pouvez aussi prendre des photos si les animaux ne sont pas trop éloignés du navire et dans ce cas indiquer la référence de la photo.

Dans le Formulaire E2, préciser :

- les numéros de session d'observation et de leg

- l'heure de début d'observation, qui sera la seule répertoriée si l'observation est très courte. Par contre si l'observation dure quelques minutes, noter l'heure de fin d'observation.

- cocher le type d'observation : visuelle de l'observateur ou signalée par un membre d'équipage aux jumelles.

- l'espèce ou le groupe de mammifères marins observés

- le nombre d'individu, et si des jeunes sont repérés, leur nombre.

- la distance d'observation en mètre s'il s'agit d'une observation visuelle de l'observateur, en mille nautique s'il s'agit d'une observation donnée par l'équipage aux jumelles.

- la position des cétacés par rapport au bateau (par quart du bateau : droit devant, ou avant/bâbord, avant/tribord, arrière/bâbord, arrière/tribord).

- le numéro des photos

- le comportement des mammifères marins:
  - souffle
  - sauts
  - sondage
  - plongeon
  - nage rapide
  - nage lente
  - en chasse
  - autre (préciser dans les notes)

- leurs comportements par rapport au bateau:
  - fuite
  - attirance
  - maintien la distance
  - indifférent
  - indéterminé
  - autre (préciser dans les notes)

Matériel requis
- Formulaires E1 et E2
- Guide d'identification des cétacés (Clé simplifiée d'identification)
- Montre
- Appareil photo
- Jumelles

Contact

Pour tous renseignements supplémentaires, contacter Lauriane ESCALLE (lauriane.escalle@ird.fr)

Effort d'Observation Mammifères Marins

Formulaire E1
Version 2.2 – Janvier 2016

Nom de l'observateur :

Nom du bateau :

Numéro du bateau :

Formulaire E1 n° :

Marée du **au**

Océan :

Commentaires :

Session n°	Leg n°	Date jj/mm/aa	Heure début (GMT) hh : mm	Quadrant T.1	Latitude début dd mm	Longitude début ddd mm	Activité bateau T. 2A	Cap bateau	Vitesse bateau	T° eau	Vitesse courant	Vitesse Vent T. 4	Nébulosité T.E1	Conditions Observation Mauvaise/ Moyenne/Bonne	Heure fin (GMT) hh : mm	Quadrant T.1	Latitude fin dd mm	Longitude fin ddd mm	Leg positif + négatif -	Raison d'interruption du leg Changement d'activité (1), de direction (2), préparation calée(3), autres (4). Cocher				Notes
																				1	2	3	4	

Données vérifiées :

Observations Mammifères Marins

Formulaire E2
Version 2.2 – Janvier 2016

Nom de l'observateur :

Nom du bateau :

Numéro du bateau :

Formulaire E2 n° :

Marée du **au**

Session n°	**Leg** n°	**Heure début (GMT)** hh mm	**Heure fin (GMT)** hh mm (facultatif)	**Observation :** (cocher) Visuelle par l'observateur (1) De l'équipage aux jumelles (2)		**Espèce ou groupe**	**Nombre** (Meilleure estimation)	**Nombre de jeunes** (facultatif)	**Distance** (mètres ou mille nautique)	**Position**	**Photo** n° (facultatif)	**Comportement** des individus	**Comportement** par rapport au bateau	**Notes**
				1	**2**									

Données Vérifiées :

Clé simplifié de détermination à la mer des Cétacés des Océans Indien et Atlantique tropicaux

A destination des observateurs scientifiques des pêches

Cette clé permet d'observer séparément différents caractères physiques précis, discriminant les espèces de mammifères marins pouvant être rencontrées.

En général, se concentrer successivement sur les caractères suivants :

1. **la taille**
2. **la forme générale du corps**
3. **la tête : absence /présence de bec**
4. **la nageoire dorsale : position, forme, couleur**
5. **la couleur et le motif de la robe**
6. **le souffle (pour les baleines)**
7. **la queue : forme, taille**
8. **le comportement en surface**
9. **le nombre d'individu (solitaire, ou taille du groupe)**

Source : Inconnu ; modifié par Lauriane Escalle

Version 2.2 – Janvier 2016

Niveau d'identification

L'identification des cétacés en mer n'est pas évidente, notamment pour des non spécialistes. En cas de doute sur une identification, préférer noter le « groupe » ou le genre auquel appartiennent les cétacés observés, éventuellement accompagné d'une description et de photos.

Groupes :

- **Mysticètes** (code MYS) : toutes les espèces de baleines (dont le petit rorqual *Balaenoptera acutorostrata)*
  Les plus rencontrés étant les Rorquals (ROR) et les Baleines à bosse (HUW), concentrer vous sur la différenciation de ces 2 groupes

- **Grands Odontocètes** (GOD) : cachalots

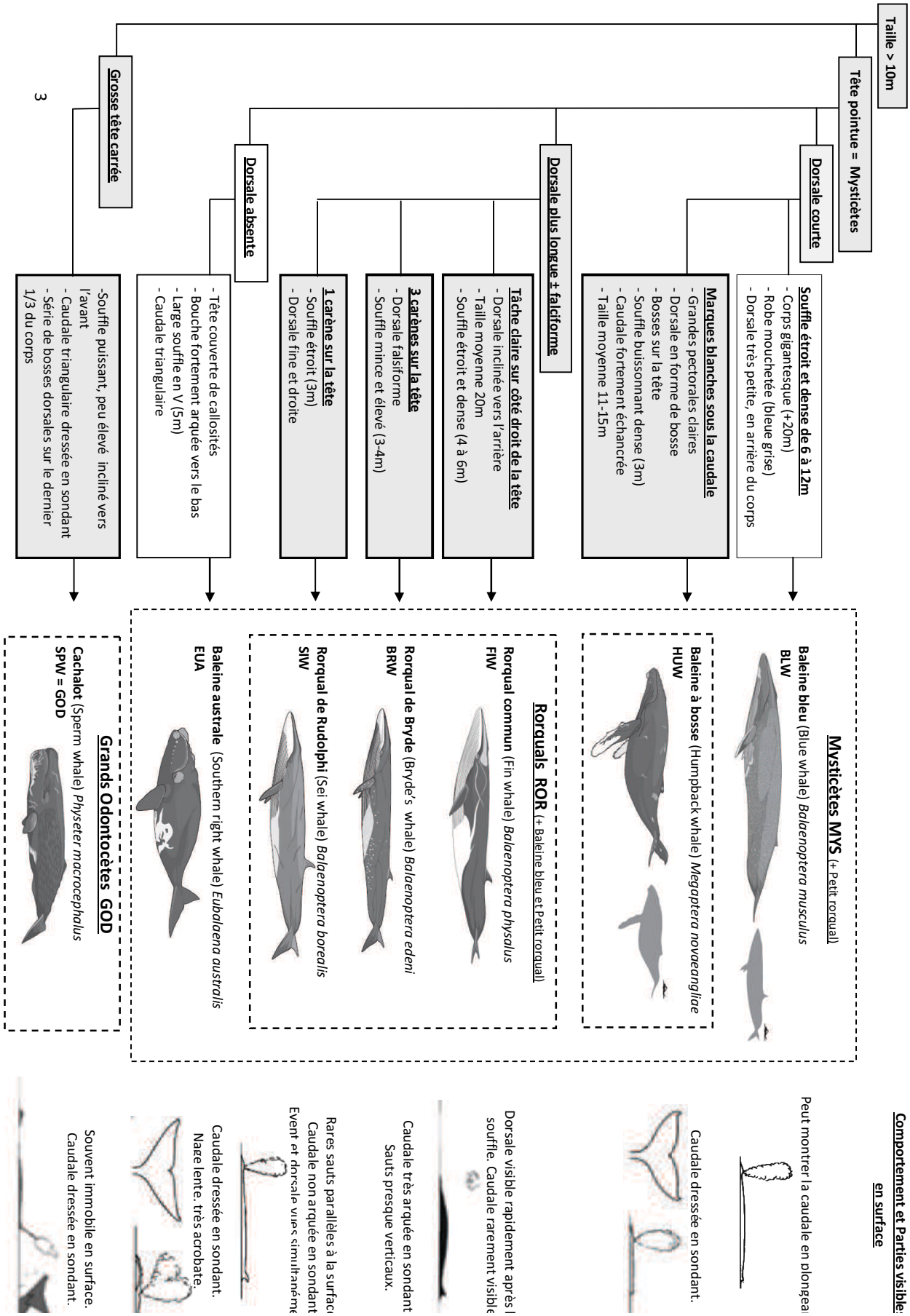
- **Petits Odontocètes** (POD) : toutes les espèces de mammifères marins de taille < 10 m, sauf le petit rorqual *Balaenoptera acutorostrata*
  Différents sous groupes peuvent être différenciés : dauphins (DEL), baleines à bec (BWH), Kogiidae (KOG), Blaskfish (BLF).

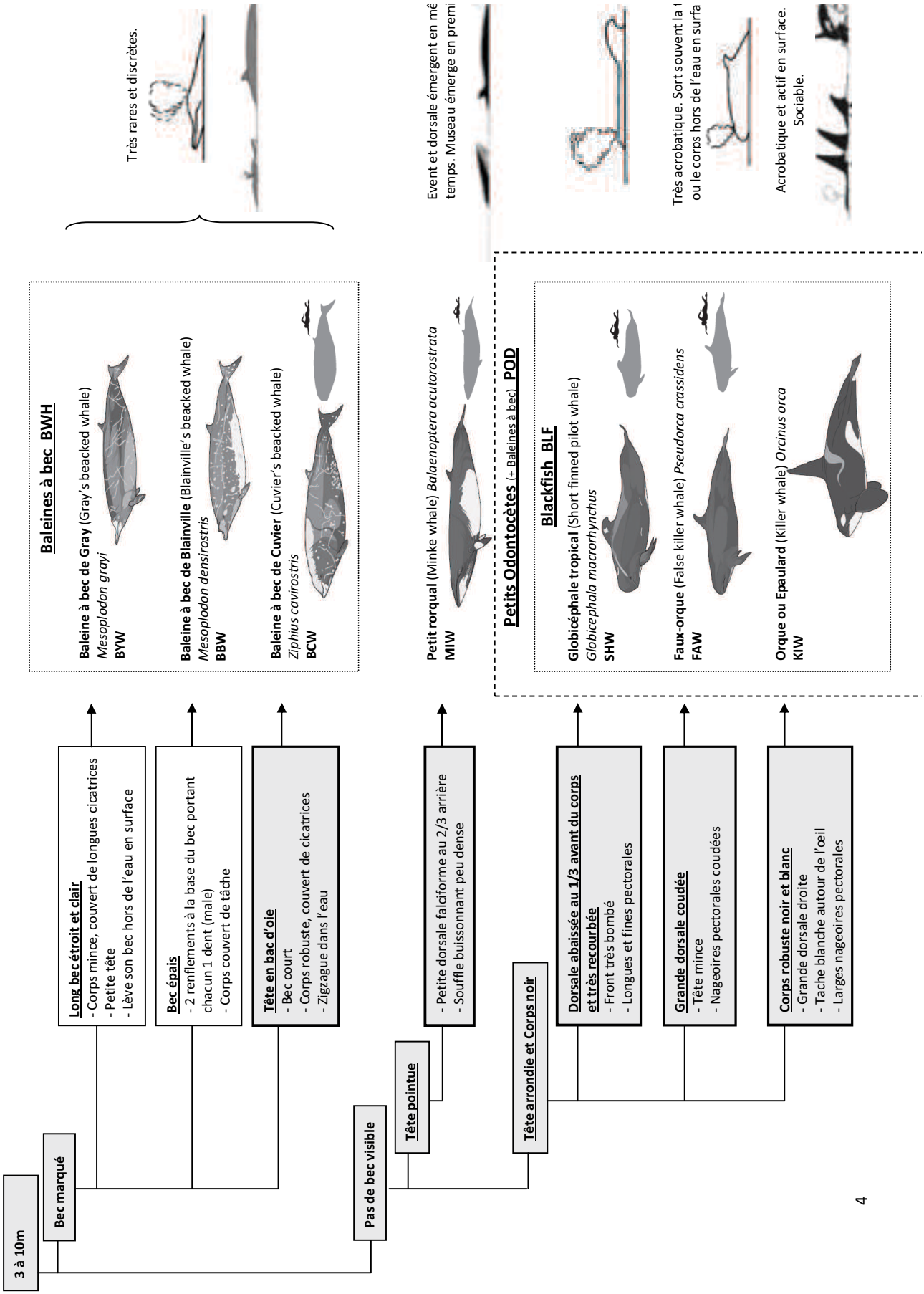
Utilisation de la clé

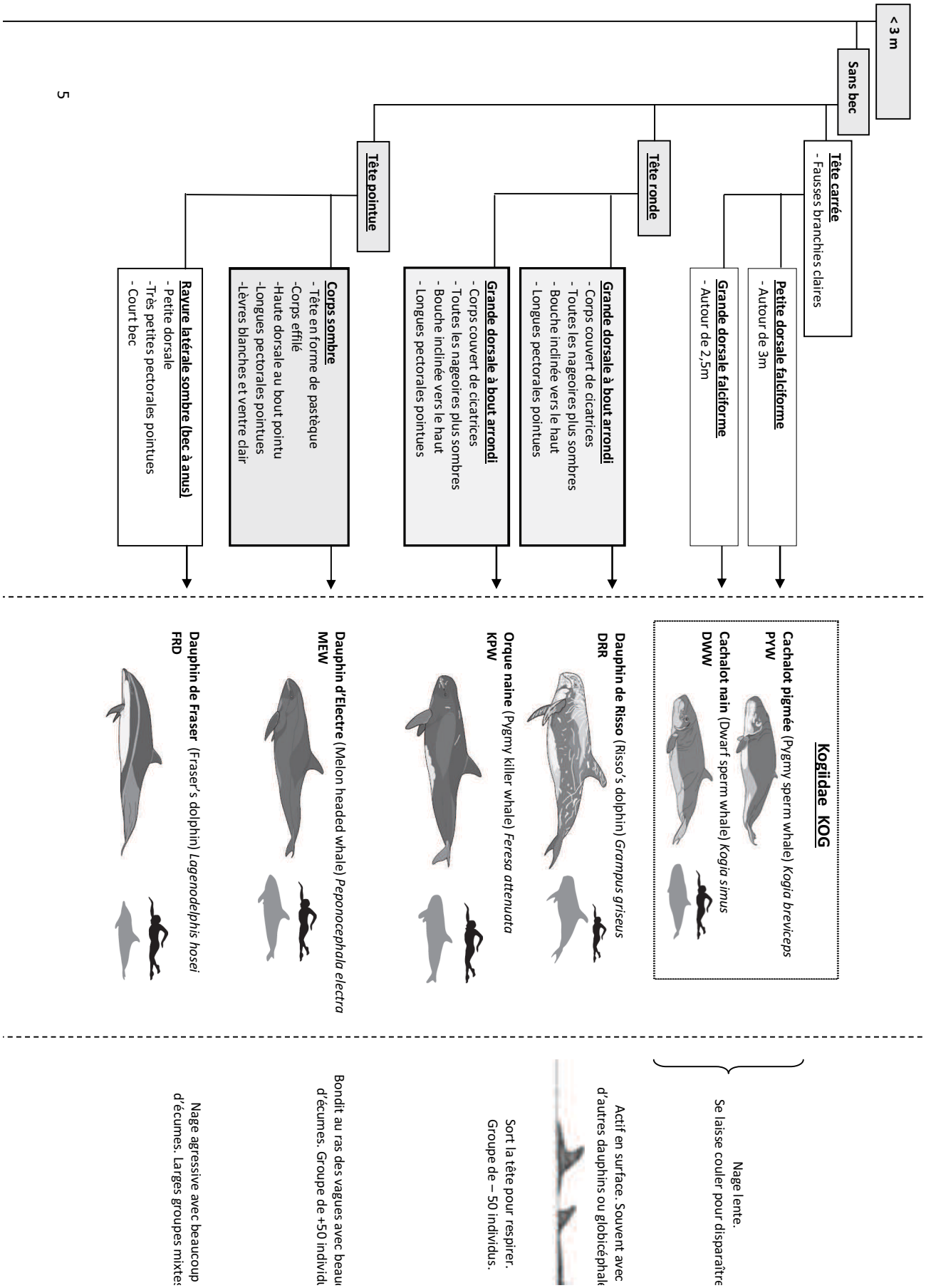
- **Chaque rectangle est une question, si la réponse est oui, passer au critère suivant (à droite), sinon descendre pour voir l'autre possibilité dans la même colonne.**
- **Les espèces associées à un cadre grisé sont les plus couramment rencontrées, les autres sont plus rares.**
- **Les indications à droite concernent les comportements des animaux en surface et peuvent aider à l'identification.**
- **La plupart des espèces sont présentes dans les 2 océans, sauf si leur répartition est précisée : océan Atlantique (OA) ou océan Indien (OI).**
- **Le nom français, anglais et scientifique de l'espèce sont notés, puis le code FAO (3 lettres) est indiqué. Utiliser ce code (ou le code du groupe) pour se référer à ces espèces dans les formulaires.**

Recommandation pour la prise de photos

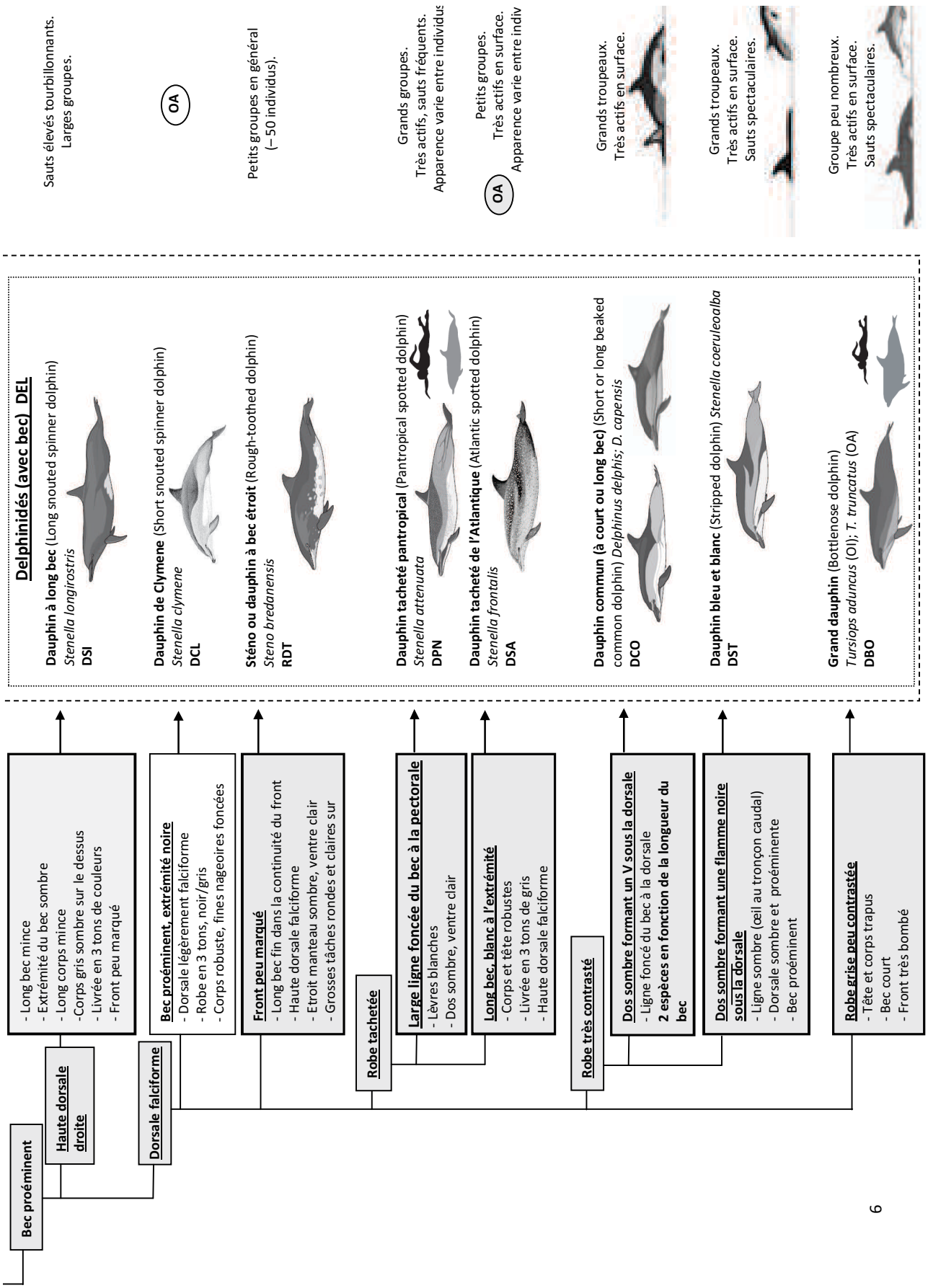
- **Prendre une photo la plus générale de l'animal et/ou du groupe**
- **Suivant la clé d'identification, essayer d'avoir une photo des caractères différenciant, en général, prendre une photo de la tête (bec ou non), dorsale, queue si elle est visible et du flanc**
- **Dans le cas des baleines, prendre une photo du souffle, s'il est visible, et de toute partie émergée**


Taille > 10m
Tête pointue = Mysticètes
Dorsale courte
Souffle étroit et dense de 6 à 12m
- Corps gigantesque (+20m)
- Robe mouchetée (bleue grise)
- Dorsale très petite, en arrière du corps
Marques blanches sous la caudale
- Grandes pectorales claires
- Dorsale en forme de bosse
- Bosses sur la tête
- Souffle buissonnant dense (3m)
- Caudale fortement échancrée
- Taille moyenne 11-15m
Dorsale plus longue ± falciforme
Tâche claire sur côté droit de la tête
- Dorsale inclinée vers l'arrière
- Taille moyenne 20m
- Souffle étroit et dense (4 à 6m)
3 carènes sur la tête
- Dorsale falsiforme
- Souffle mince et élevé (3-4m)
1 carène sur la tête
- Souffle étroit (3m)
- Dorsale fine et droite
Dorsale absente
- Tête couverte de callosités
- Bouche fortement arquée vers le bas
- Large souffle en V (5m)
- Caudale triangulaire
Grosse tête carrée
-Souffle puissant, peu élevé incliné vers l'avant
- Caudale triangulaire dressée en sondant
- Série de bosses dorsales sur le dernier 1/3 du corps
3
Mysticètes MYS (+ Petit rorqual)
Baleine bleu (Blue whale) Balaenoptera musculus
BLW
Baleine à bosse (Humpback whale) Megaptera novaeangliae
HUW
Rorquals ROR (+ Baleine bleu et Petit rorqual)
Rorqual commun (Fin whale) Balaenoptera physalus
FIW
Rorqual de Bryde (Bryde's whale) Balaenoptera edeni
BRW
Rorqual de Rudolphi (Sei whale) Balaenoptera borealis
SIW
Baleine australe (Southern right whale) Eubalaena australis
EUA
Grands Odontocètes GOD
Cachalot (Sperm whale) Physeter macrocephalus
SPW = GOD
Comportement et Parties visibles en surface
Peut montrer la caudale en plongeai
Caudale dressée en sondant.
Dorsale visible rapidement après l souffle. Caudale rarement visible
Caudale très arquée en sondant Sauts presque verticaux.
Rares sauts parallèles à la surfac Caudale non arquée en sondant Event et dorsale vues simultanéme
Caudale dressée en sondant. Nage lente. très acrobate.
Souvent immobile en surface. Caudale dressée en sondant.


3 à 10m
Bec marqué
Long bec étroit et clair
- Corps mince, couvert de longues cicatrices
- Petite tête
- Lève son bec hors de l'eau en surface
Bec épais
- 2 renflements à la base du bec portant chacun 1 dent (male)
- Corps couvert de tâche
Tête en bac d'oie
- Bec court
- Corps robuste, couvert de cicatrices
- Zigzague dans l'eau
Baleines à bec BWH
Baleine à bec de Gray (Gray's beacked whale)
Mesoplodon grayi
BYW
Baleine à bec de Blainville (Blainville's beacked whale)
Mesoplodon densirostris
BBW
Baleine à bec de Cuvier (Cuvier's beacked whale)
Ziphius cavirostris
BCW
Très rares et discrètes.
Pas de bec visible
Tête pointue
- Petite dorsale falciforme au 2/3 arrière
- Souffle buissonnant peu dense
Petit rorqual (Minke whale) Balaenoptera acutorostrata
MIW
Tête arrondie et Corps noir
Dorsale abaissée au 1/3 avant du corps et très recourbée
- Front très bombé
- Longues et fines pectorales
Grande dorsale coudée
- Tête mince
- Nageoires pectorales coudées
Corps robuste noir et blanc
- Grande dorsale droite
- Tache blanche autour de l'œil
- Larges nageoires pectorales
Petits Odontocètes (+ Baleines à bec) POD
Blackfish BLF
Globicéphale tropical (Short finned pilot whale)
Globicephala macrorhynchus
SHW
Faux-orque (False killer whale) Pseudorca crassidens
FAW
Orque ou Epaulard (Killer whale) Orcinus orca
KIW
Event et dorsale émergent en mê
temps. Museau émerge en premi
Très acrobatique. Sort souvent la t
ou le corps hors de l'eau en surfa
Acrobatique et actif en surface.
Sociable.
4


< 3 m
Sans bec
Tête carrée
- Fausses branchies claires
Petite dorsale falciforme
- Autour de 3m
Grande dorsale falciforme
- Autour de 2,5m
Tête ronde
Grande dorsale à bout arrondi
- Corps couvert de cicatrices
- Toutes les nageoires plus sombres
- Bouche inclinée vers le haut
- Longues pectorales pointues
Grande dorsale à bout arrondi
- Corps couvert de cicatrices
- Toutes les nageoires plus sombres
- Bouche inclinée vers le haut
- Longues pectorales pointues
Tête pointue
Corps sombre
- Tête en forme de pastèque
-Corps effilé
-Haute dorsale au bout pointu
-Longues pectorales pointues
-Lèvres blanches et ventre clair
Rayure latérale sombre (bec à anus)
- Petite dorsale
-Très petites pectorales pointues
- Court bec
Kogiidae KOG
Cachalot pigmée (Pygmy sperm whale) Kogia breviceps
PYW
Cachalot nain (Dwarf sperm whale) Kogia simus
DWW
Dauphin de Risso (Risso's dolphin) Grampus griseus
DRR
Orque naine (Pygmy killer whale) Feresa attenuata
KPW
Dauphin d'Electre (Melon headed whale) Peponocephala electra
MEW
Dauphin de Fraser (Fraser's dolphin) Lagenodelphis hosei
FRD
Nage lente.
Se laisse couler pour disparaître
Actif en surface. Souvent avec
d'autres dauphins ou globicéphale
Sort la tête pour respirer.
Groupe de – 50 individus.
Bondit au ras des vagues avec beau
d'écumes. Groupe de +50 individu
Nage agressive avec beaucoup
d'écumes. Larges groupes mixtes

5


Bec proéminent
Haute dorsale droite
- Long bec mince
- Extrémité du bec sombre
- Long corps mince
-Corps gris sombre sur le dessus
- Livrée en 3 tons de couleurs
- Front peu marqué
Dorsale falciforme
Bec proéminent, extrémité noire
- Dorsale légèrement falciforme
- Robe en 3 tons, noir/gris
- Corps robuste, fines nageoires foncées
Front peu marqué
- Long bec fin dans la continuité du front
- Haute dorsale falciforme
- Etroit manteau sombre, ventre clair
- Grosses tâches rondes et claires sur
Robe tachetée
Large ligne foncée du bec à la pectorale
- Lèvres blanches
- Dos sombre, ventre clair
Long bec, blanc à l'extrémité
- Corps et tête robustes
- Livrée en 3 tons de gris
- Haute dorsale falciforme
Robe très contrasté
Dos sombre formant un V sous la dorsale
- Ligne foncé du bec à la dorsale
2 espèces en fonction de la longueur du bec
Dos sombre formant une flamme noire sous la dorsale
- Ligne sombre (œil au tronçon caudal)
- Dorsale sombre et proéminente
- Bec proéminent
Robe grise peu contrastée
- Tête et corps trapus
- Bec court
- Front très bombé
Delphinidés (avec bec) DEL
Dauphin à long bec (Long snouted spinner dolphin)
Stenella longirostris
DSI
Dauphin de Clymene (Short snouted spinner dolphin)
Stenella clymene
DCL
Sténo ou dauphin à bec étroit (Rough-toothed dolphin)
Steno bredanensis
RDT
Dauphin tacheté pantropical (Pantropical spotted dolphin)
Stenella attenuata
DPN
Dauphin tacheté de l'Atlantique (Atlantic spotted dolphin)
Stenella frontalis
DSA
Dauphin commun (à court ou long bec) (Short or long beaked common dolphin) Delphinus delphis; D. capensis
DCO
Dauphin bleu et blanc (Stripped dolphin) Stenella coeruleoalba
DST
Grand dauphin (Bottlenose dolphin)
Tursiops aduncus (OI); T. truncatus (OA)
DBO
Sauts élevés tourbillonnants.
Larges groupes.
OA
Petits groupes en général
(– 50 individus).
Grands groupes.
Très actifs, sauts fréquents.
Apparence varie entre individus
Petits groupes.
Très actifs en surface.
Apparence varie entre indiv
OA
Grands troupeaux.
Très actifs en surface.
Grands troupeaux.
Très actifs en surface.
Sauts spectaculaires.
Groupe peu nombreux.
Très actifs en surface.
Sauts spectaculaires.
6

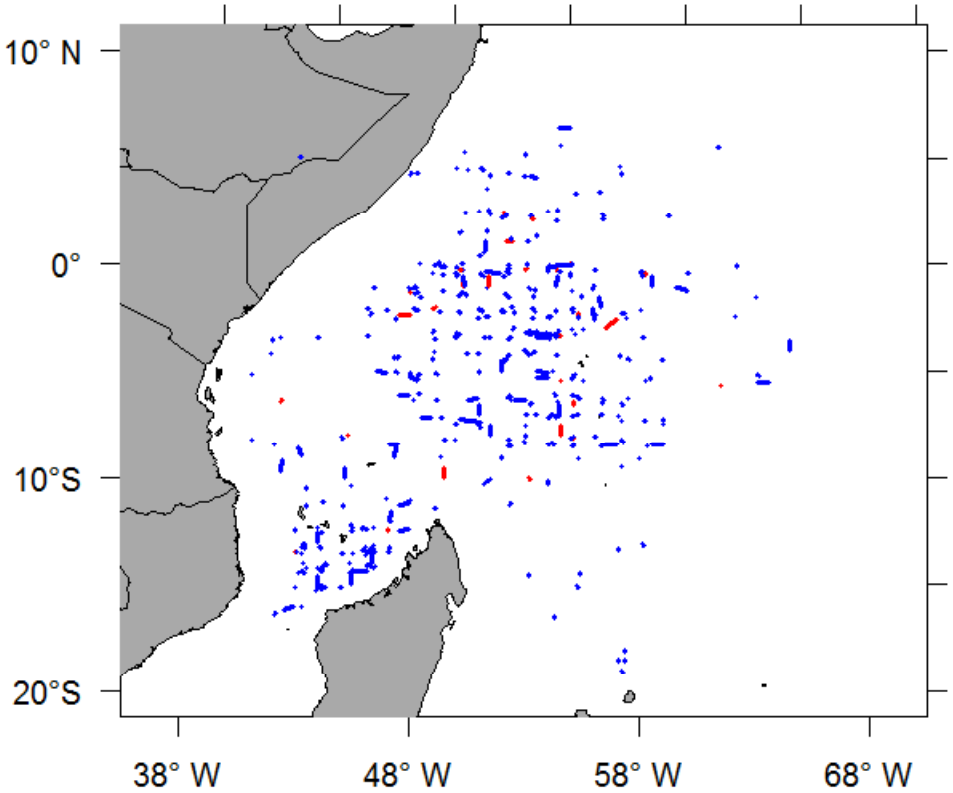
Observations de cétacés réalisées par des observateurs scientifiques à bord des thonniers senneurs dans l'océan Indien en 2014 et 2015.

Sessions d'observations effectuées à bord des thonniers senneurs dans le cadre du protocole d'observations des mammifères marins.

Nombre de marées avec sessions d'observations	Nombre de jours en mer	Nombre de sessions d'observations effectuées	Nombre de legs	Nombre de legs avec observation	Durée totale d'observation (heure)	Nombre d'observations de cétacés
18	737	407	534	33	204	37

Espèces ou groupes d'espèces observées lors de sessions d'observations.

Espèce ou groupe	Nombre d'observations	Nombre d'individus estimé
Cétacés non identifiés	2	3
Petits odontocètes	13	230
Dauphins	14	760
Delphinus delphis	2	3
Tursiops aduncus	1	15
Mysticètes	4	5
Balaenoptera physalus	1	2



Legs (bleu: sans observation, rouge: avec observation de cétacés) observés en 2014 et 2015 par des observateurs scientifiques à bord des thonniers senneurs.

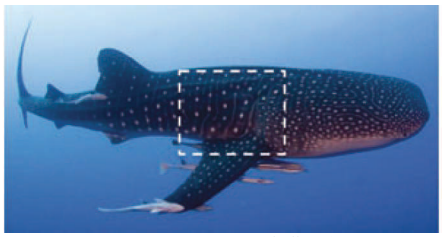
Version 1 – Mars 2014

Opération Photo-Identification Requins Baleines et Raies Manta[1]

(complément au guide de prise de vues)

Requin Baleine

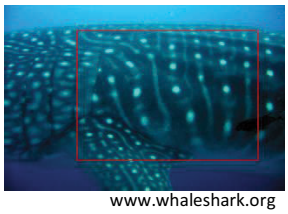
Le motif formé par les tâches blanches est unique pour chaque animal, notamment la partie située à l'arrière des fentes branchiales. Une photo claire de cette zone peut donc permettre de reconnaitre un individu particulier.



Marshall and Pierce, 2012

Prises de photos :

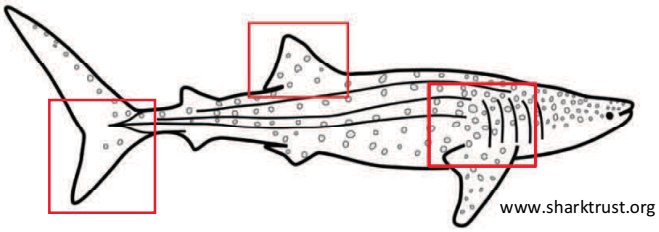
- De la **zone à l'arrière des fentes branchiales** (zone clé), si possible sur le côté gauche de l'animal, ou des 2 côtés



www.whaleshark.org

Se positionner de manière à être perpendiculaire à cette zone, et zoomer le plus possible. Comme sur la photo ci-dessus.

- D'éventuelles cicatrices, déformations ou blessures
- De la nageoire dorsale, ou caudale si elles sont visibles
- De l'animal en entier
- Noter le sexe (présence ou absence de ptérygopodes) si possible, et une estimation de sa taille (par exemple en se basant le nombre de flotteur de la ralingue supérieure du filet)

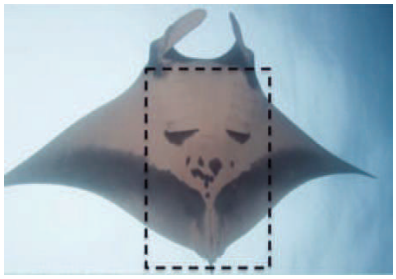


www.sharktrust.org

[1] Source : Lauriane ESCALLE (lauriane.escalle@ird.fr)

Raie manta

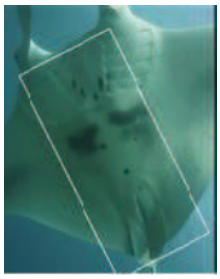
Une identification peut également être réalisée en se basant sur le motif de la partie ventrale de l'animal. Si un individu est remonté à bord, prendre des photos avant qu'il ne soit remis à l'eau.



www.mantamatcher.org

Prises de photos :

- De la partie dorsale de l'animal, faire un zoom sur des motifs particuliers, cicatrices ou blessures
- Si cela est possible sans risquer de blesser l'animal, le retourner sur le dos, **la partie clé pour l'identification étant la partie ventrale**
- Positionnez vous le plus possible au dessus de l'animal, pour avoir une vue d'ensemble
- Prendre une photo
    - de la partie entre les fentes branchiales
    - du ventre
    - des nageoires pelviennes (sexe de l'animal)



Other thesis contributions - Conferences and working groups

Escalle, L., Chavance, P., Gaertner, D., Capietto, A., Pennino, M.G., Dubroca, L., Murua, H., Delgado De Molina, A., Demarcq, H., Spitz, J., Kiszka, J., Floch, L., Damiano, A., Romanov, E., Mérigot, B. (2015) Spatio-temporal interactions between cetaceans and tuna purse seine fisheries with link to environmental factors in the Atlantic and Indian Oceans. 21st Biennial Conference on the Biology of Marine Mammals, San Francisco USA (talk)

Escalle, L., Gaertner, D., Chavance, P., Delgado de Molina, A., Ariz, J., Mérigot, B. (2015) Monte Carlo simulations of time-area moratorium on FAD set on catches and bycatches. EU project Catch, Effort, and eCOsystem impacts of FAD-fishing (CECOFAD) final meeting, Pasia, San Sebastian, Spain (talk)

Escalle, L., Capietto, A., Chavance, P., Dubroca, L., Delgado De Molina, A., Murua, H., Amandé, J.M., Gaertner, D., Filmalter J.D., Forget, F., Rowat, D., Dagorn, L., Mérigot, B. (2015) Megafauna and purse seine fisheries: interactions and survival of the whale shark, the world's largest fish. 27th International Congress on Conservation Biology, Montpellier, France (talk)

Escalle, L., Capietto, A., Chavance, P., Dubroca, L., Delgado De Molina, A., Murua, H., Gaertner, D., Romanov, E., Rowat, D., Spitz, J., Kiszka, J., Mérigot, B. (2015) Interactions entre mammifères marins, requin baleine et pêche thonière tropicale. 12ème Congrès de l'association française d'halieutique, Montpellier, France (talk)

Escalle L., Capietto A., Chavance P., Dubroca L., Delgado De Molina A., Murua H., Gaertner D., Romanov E., Spitz J., Kiszka J., Floch L., Damiano A., Mérigot B. (2015) Cetaceans and tuna fishery in the Atlantic and Indian Oceans: interaction but few mortalities. 29th Annual Conference of the European Cetacean Society, La Valette, Malta (poster)

Escalle, L., Chavance, P., Amandé, J.M., Filmalter, J.D., Forget, F., Gaertner, D., Dagorn, L., Mérigot, B. (2014) Post-capture survival of whale sharks released from purse seine nets: preliminary results from tagging experiment. Collective Volume of Scientific Papers ICCAT SCRS/2014/135

Escalle, L., Chavance, P., Amandé, J.M., Filmalter, J.D., Forget, F., Gaertner, D., Dagorn, L., Mérigot, B. (2014) Etude de la survie de requins baleine après encerclement par des thoniers senneurs: méthode et résultats préliminaires. Note d'information aux équipages des thoniers senneurs tropicaux