Effects of the fishing strategies developed by purse seine fleets on tropical tunas and on associated fauna in the eastern Atlantic and eastern Pacific oceans.

Effets des stratégies de pêche développées par les flottes de senneurs sur les thons tropicaux et sur la faune associée dans l'Atlantique Est et dans le Pacifique Est.

Thèse de doctorat, spécialité Écosystèmes,
présentée devant l'Université Montpellier 2 par

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15 Juin 2012

CRH Sète, UMR EME 212

Jury :

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THESE DE DOCTORAT DE L'UNIVERSITE MONTPELLIER 2

Spécialité : Écosystèmes (École Doctorale SIBAGHE -*Systèmes intégrés en Biologie, Agronomie, Géosciences, Hydrosciences et Environnement*-)

Présenté par : Edgar TORRES IRINEO

Pour obtenir le grade de : DOCTEUR de l'UNIVERSITE DE MONTPELLIER 2

Sujet de la thèse :

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Soutenue le 15 Juin 2012

Devant le jury composé de :

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Abstract

Tuna and tuna-like fisheries represent 7.9% of the global production of marine capture fisheries. Most tuna stocks are fully exploited and some overexploited, facing growing fishing pressures. Due to the extent of fishing grounds, stock assessments depend largely in commercial data, which vary over time because fishermen may invest in fishing technology, expand offshore, or start fishing in different areas. However, little attention has received the responses of fishermen facing management regulations or the effects resulting from technological investment. For these reasons the aim of this study was to investigate the effects of fishing strategies developed by purse seine fleets on tropical tunas and on associated fauna in the eastern Atlantic and eastern Pacific oceans. The continuous introduction of new fishing technology in the French fleet in the 1980s and the 1990s evidenced a direct increase in fishing power when large yellowfin in free-swimming school is targeted and likely an indirect effect by modifying the fishing grounds characterizing FAD-fishing on small size categories. The consequences of the two time-area closures on the spatio-temporal dynamics of the European Union fleet were investigated. The regulation on FADs resulted in a decrease in the days with catch and successful squares inside the restricted area, reallocating FAD-fishing outside the area while no change in free-swimming school fishing was observed. The no-take time-area increased all fishing activities outside the restricted area with apparently no gain in terms of protection of juveniles. In the eastern Pacific as a response to a closed season the Mexican fleet reduced days in port and consequently the number of sets on dolphin-associated schools increased, maintaining the catch levels observed before the regulation. The study of the effects of the EU fleet fishing strategies on bycatch over two time periods showed that the species composition of sharks caught on FADs and may be for rays caught on free-swimming schools changed over time. We also estimated the total number of species that can be potentially be caught by fishing mode.

Key words Tropical tunas, purse seine fishery, fishing strategies and tactics, fleet dynamics, introduction of fishing technology, spatio-temporal regulations, bycatch, eastern tropical Atlantic, eastern tropical Pacific.

Résumé

Les pêcheries de thonidés représentent 7.9% de la production mondiale de produits de la mer. La plupart des stocks de thons sont pleinement exploités, et certains surexploités, et tous font face à une pression de pêche croissante. En raison de l'extension des zones de pêche, les évaluations des stocks dépendent en grande partie des captures commerciales. Toutefois, les données commerciales peuvent varier au cours du temps étant donné que les pêcheurs peuvent investir dans des engins de pêche et de l'équipement, s'établir au large des côtes, ou commencer à pêcher dans de nouvelles zones. Peu d'attention a été portée à la réponse des pêcheurs aux mesures de gestion ou aux conséquences de l'investissement technologique. L'objectif de la présente thèse est d'étudier les effets de stratégies de pêche et les réponses adaptatives des flottes de senneurs sur les thons tropicaux et la faune associée dans l'Océan Atlantic Est et dans l'Océan Pacifique Est. Dans un premier temps, nous montrons comment l'introduction de nouvelles technologies a eu un effet direct en augmentant la puissance de pêche, et un effet indirect en entraînant une modification des zones pêche. Nous étudions les effets de deux fermetures spatio-temporelles sur la dynamique de la flotte de senneurs européens. La première mesure de gestion a diminué les jours où des captures sont réalisées, les carrés avec capture à l'intérieur de la zone partiellement fermée, tandis que la pêche sur DCP a été redistribuée à l'extérieur de la zone et aucun changement n'a pas été enregistré pour la pêche sur banc libre. La seconde fermeture de pêche a entraîné une augmentation de toutes les activités de pêche en dehors de la zone. Dans l'Océan Pacifique Est, la flotte de senneurs mexicains a réagit à la fermeture d'une saison de pêche en diminuant le nombre de jours passés à quai. Par conséquent, le nombre de calées sur bancs associés aux dauphins a augmenté, et les niveaux de capture observés avant la mesure de gestion ont été maintenues. Nous analysons les effets des stratégies de senneurs de l'Union Européenne sur les prises accessoires. Nous mettons en évidence que la composition des espèces de requins capturés sous DCP et les raies capturées sur bancs libres ont changé au cours du temps. Nous estimons également que plusieurs types d'espèces peuvent être capturés par mode de pêche.

Mots-clés Thons tropicaux, la pêche à la senne, les stratégies et les tactiques de pêche, la dynamique de la flotte, introduction de la technologie de la pêche, régulations spatio-temporelles, pris accessoires, Atlantic tropical Est, Pacifique tropical Est.

Acknowledgments

This study is part of the Mexico-France program of research in marine science and fisheries. The work was possible by a PhD grant (No. 199730) offered by The National Council on Science and Technology of Mexico (CONACYT).

I would like to acknowledge the following people for their support throughout this project: First of all, Daniel Gaertner, for all his support, guidance, and time dedicated to this project, for being not only an extraordinary supervisor but also a very good friend, helping me every time when I need it. I would like to thank Michel Dreyfus for all your support and time dedicated along my study stay in Ensenada, Mexico. I want to thank "l'observatoire thoniere" for providing the French purse seine fleet logbook data and observer data used in this study, especially Pierre Chavance and Laurent Floch. I want to thank the IEO for providing Spanish logbook data and observer data used in some analyses of this study, especially Javier Ariz and Alicia Delgado. My gratitude also goes to AZTI for providing observer data, especially Hilario Murua and Nerea Lezama. I want to thank FIDEMAR-PNAAPD for providing observer data of the Mexican purse seine fleet. I would like to thank ORTHONGEL, French tuna boat owners association and SAUPIQUET, French tuna producer for their close cooperation providing information about the introduction of technology on French purse seiners, especially Michel Goujon and Anthony Claude, respectively.

I want to thank Francis Laloë, Catherine Aliaume for their comments and valuable feed-back during the meetings carried out along this study. I would like acknowledge Tang Do Chi (RIP) for helping me since the first time when I was visited France looking for a PhD program. I am very grateful to Silvia Salas for encouraging me to do my PhD in France, for trusting me, guide me and especially for being a great friend and professor.

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A. Introduction

Les captures totales de thonidés représentent 7.9% de la production mondiale des pêcheries marines (FAO 2010). Le listao (*Katsuwonus pelamis*), l'albacore (*Thunnus albacares*) et le patudo (*Thunnus obesus*) sont les espèces des thons les plus capturées avec 3,97 millions de tonnes. Les thonidés tropicaux sont ciblés des flottilles industrielles qui utilisent différents engins de pêche, tels que la palangre qui cible surtout le gros patudo et le gros albacore, la pêche à appât vivant pratiquée par les canneurs qui ciblent principalement le listao, mais aussi selon la zone l'albacore et le patudo, et enfin la pêche à la senne qui cible principalement l'albacore et le listao. A partir des années 1980, la pêche à la senne est devenue plus importante que la pêche à la palangre et que la pêche à appât vivant.

Les espèces de thon sont hautement migratoires et leur disponibilité varie dans l'espace et dans le temps (Cayré et al. 1993; Lehodey et al. 1997). Les thons se regroupent pour former des bancs qui à leur tour, lorsque les conditions de l'environnement sont appropriées, se rassemblent en grandes concentrations (Stretta 1993; Ravier et al. 2000; Fonteneau et al. 2008). Au cours des différentes étapes de la pêche chaque pêcheur peut choisir plusieurs options pour utiliser au mieux les ressources, mais les limites imposées par la variabilité de l'environnement ou du marché peuvent influer sur la façon dont les pêcheurs planifient cette exploitation (Salas & Gaertner 2004). En conséquence, en réponse à leurs objectifs mais aussi aux contraintes qu'ils rencontrent par rapport aux contextes économiques, sociaux et culturels, les pêcheurs développent et mettent en œuvre des tactiques, sur le court terme, qui se combinent en stratégies au cours de la saison de pêche.

La majorité des stocks de thons sont pleinement exploités, voire surexploités, et tous font face à une pression de pêche croissante. La conservation et la gestion de ces espèces hautement migratrices se complique par la nature transnationale des stocks de thon. D'une part, ces stocks sont partagés entre les zones économiques exclusives (ZEE) de différents pays, mais ils sont également distribués aussi au-delà des ZEE (environ 40% des captures de mondiales thons sont faites en haute mer). Face à ce contexte plusieurs organisations régionales de gestion de la pêche (ORGP) ont été mises en place pour gérer les pêcheries thonières au sein d'un contexte régional, ou par océan. Dans les pêcheries établies ou matures, telles que les pêcheries au thon, les ORGP tendent à se concentrer sur la façon d'évaluer l'état des stocks et sur la façon de contrôler la capture ou l'effort de pêche. Les évaluations des stocks fournissent des recommandations sur le niveau d'exploitation appropriée des stocks de poissons, mais les gestionnaires des pêcheries

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[1] Les figures et tables référencées dans ce résumé correspondent à celles du texte principal de cette thèse.

doivent choisir la façon de contrôler le niveau d'exploitation (Branch et al. 2006). La gestion commence souvent par des contrôles d'entrée et notamment par des restrictions sur la longueur de la saison de pêche, le tonnage, les types d'engins, et l'entrée des navires dans la pêcherie. Toutefois, les contrôles d'entrée aboutissent presque toujours à une pêche moins efficace (à la fois techniquement et économiquement), car elles restreignent les méthodes de capture au lieu de restreindre la capture directement (Salas & Gaertner 2004).

Traditionnellement, les données d'entrée utilisées dans l'évaluation des stocks proviennent : (1) des pêcheries, par exemple : la capture par unité d'effort (CPUE) et les fréquences de taille des captures ; et (2) des données indépendantes de la pêche généralement obtenues à partir de campagnes scientifiques (ce qui n'est pas le cas pour les thons). L'adéquation des données commerciales pour suivre l'état des stocks change avec l'évolution de la pêcherie parce que les pêcheurs peuvent investir dans la modernisation des engins de pêche et dans les équipements et s'établir dans de nouvelles zones (Branch et al. 2006). En conséquence, ignorer le comportement des pêcheurs dans les modèles d'évaluation des stocks peut entraîner une mauvaise perception de la dynamique de la pêcherie (Pelletier & Ferraris 2000).

Selon Hilborn & Walters (1992) la dynamique d'une flotte peut être divisée en quatre parties distinctes : (1) l'investissement de la pêche, (2) l'allocation spatio-temporelle de l'effort de pêche, (3) les déterminants de la puissance de pêche et (4) les déterminants des rejets. Dans ce contexte, l'objectif de cette étude est d'explorer la dynamique des flottes thonières à la senne européenne et mexicaine qui sont respectivement parmi les flottes thonières de surface les plus importantes dans l'Océan Atlantique Est et dans l'Océan Pacifique Est, et de mettre en évidence les facteurs internes (e.g., nouvelles technologies de pêche pour la flotte française) ou externes (e.g., mesures de gestion spatio-temporelles) qui ont influé sur la distribution spatiale des flottes et des modes de pêche. Ces flottes de senneurs sont exposées à différentes conditions environnementales dans chaque océan. L'Océan Atlantique se caractérise par une forte saisonnalité tandis que dans l'Océan Pacifique la principale caractéristique est la variabilité interannuelle, largement influencée par des anomalies de type El Niño. Dans ces conditions océaniques spécifiques, chaque flotte a développé des stratégies de pêche différentes pour capturer le thon : la flotte de senneurs français pêche sur banc libre et sur des Dispositifs de Concentration de Poissons (DCP), tandis que la flotte de senneurs mexicains pêche sur des bancs associés à des dauphins.

Dans ce travail, nous avons étudié différentes facettes de la dynamique des flottes afin de montrer les effets des stratégies de pêche et des réponses adaptatives des flottes de senneurs sur les thons tropicaux et sur la faune associée dans ces deux océans. Nous avons donc étudié (1) les effets de l'introduction de nouvelles technologies à bord des senneurs français sur les stratégies et tactiques de pêche, (2) les effets de la mise en œuvre de mesures de gestion spatio-temporelles sur la flotte européenne et de la fermeture d'une saison de pêche sur la flotte mexicaine. En ce qui concerne la flotte européenne, deux mesures spatiales ont été mises en place. La première mesure consistait en l'interdiction de la pêche sur DCP sur d'une grande partie du Golfe de Guinée pendant trois mois (novembre-janvier), de 1997 jusqu'à 2004. La deuxième mesure a interdit à partir de 2005toute capture de surface dans la zone Picolo pour le seul mois de novembre. Dans le Pacifique Est, les senneurs mexicains ont du faire face à la fermeture de la saison de pêche en décembre, à partir de 2002. Nous avons également étudié les effets des nouvelles stratégies de pêche de la flotte européenne sur la faune associée. Pour cela nous avons cherché des changements dans la composition d'espèces au cours de deux périodes de temps (1997-1999 et 2005-2008), supposées refléter l'évolution technologique de cette flotte. Nous avons examiné la richesse spécifique de la faune associée par mode de pêche au cours de ces deux périodes de temps et décrit la distribution spatiale d'espèces recensées dans la liste d'espèces menacées de l'IUCN. Finalement, on a analysé la saisonnalité et les distributions spatiales des coups de sennes effectués sur des baleines et sur des requins baleines.

B. Effets des nouvelles technologies de pêche sur les stratégies et les tactiques de pêche des thoniers senneurs opérant dans l'Océan Atlantique Est

Quel que soit le domaine d'activité considéré, de nouvelles technologies ont été introduites au fil du temps afin de faciliter les activités humaines. En ce qui concerne les activités de pêche, l'utilisation de nouvelles technologies a pour objectif de capturer plus de poissons et/ou d'améliorer la qualité des débarquements. Les principaux objectifs de l'investissement par le secteur de la pêche sont de deux ordres : (1) l'augmentation des bénéfices ou l'économie sur divers domaines de leurs activités (par exemple, réduction des coûts d'exploitation, réduction du travail, amélioration de la sécurité de l'équipage), et (2) la confrontation à des mesures de gestion sur l'effort de pêche. L'investissement de la pêche fait partie du comportement de la flotte et peut consister dans l'acquisition de nouveaux navires et dans de nouvelles technologies qui se traduira par une plus grande efficacité de pêche (e.g., accroissement de la capturabilité dans les zones de pêche traditionnelles) et par la possibilité d'avoir de nouvelles tactiques (e.g., l'accès saisonnier à de nouvelles zones de pêche). En général, l'augmentation de l'efficacité de pêche et l'évolution de l'engin de pêche, ainsi que des pratiques associées, modifient la relation entre les taux de capture et l'abondance (i.e., la capturabilité au sens strict) qui constitue la base fondamentale des données d'entrée pour les modèles d'évaluation des stocks et les avis de gestion qui en résultent.

Dans ce chapitre nous avons étudié à quel point l'introduction de nouvelles technologies à bord a affecté l'efficacité de pêche de la flotte de senneurs français dans l'Océan Atlantique Est pour la période 1981-2008 et a modifié le choix des modes de pêche dans l'espace et dans le temps (i.e., les tactiques) ainsi que la séquentialité de ces dernières en cours d'année (i.e., les stratégies). A partir des données de livres de bord on a estimé pour deux indicateurs liés à chaque mode de pêche (i.e. pêche sur DCP dérivants et pêche sur bancs libres), les valeurs mensuelles pour chaque navire après normalisation par le nombre de jours de mer. L'indicateur correspondant à la pêche sur bancs libres est le nombre de calées sur bancs libres, tandis que celui correspondant à la pêche sur DCP est la prise de juvéniles sur DCP. Ces indicateurs peuvent être sensibles à des changements de la puissance de pêche individuelle des navires, à savoir qu'une augmentation de la puissance de pêche pourrait se traduire par une augmentation du nombre d'activités de pêche par jour de mer. Nous argumentons le fait que les indicateurs comprennent les effets concomitants et combinés de l'utilisation simultanée de plusieurs appareils impliqués dans la pêche à la senne.

Le recensement des principales innovations technologiques introduites à bord de la flottille de senneurs français mené à travers le projet de recherche de l'Union Européenne « Efficacité des senneurs thoniers et effort réels » (ESTHER, voir Gaertner & Pallarés 2002) a été actualisé (Figure 2.2). Au cours de cette analyse nous avons assumé que tout changement significatif dans la série temporelle de chaque indicateur pouvait être relié à l'introduction de ces innovations.

Pour répondre à l'objectif de ce chapitre nous avons utilisé différentes approches statistiques :

(1) à partir de modèles linéaires mixtes nous avons décrit des variations annuelles sur chaque indicateur. Nous avons considéré les facteurs : année, mois et bateau, afin d'extraire les effets saison et bateau. Pour le reste de l'analyse nous avons donc utilisé les valeurs des effets aléatoires du facteur année comme indicateur annuel normalisé.

(2) à partir d'une analyse bayésienne appelée « Bayesian change-point analysis » nous avons cherché les changements soudains sur ces séries d'indicateurs normalisés afin d'obtenir des périodes d'années homogènes. Nous avons fait l'hypothèse que ces périodes correspondaient à des régimes caractéristiques de chaque stratégie de pêche à la senne.

(3) à partir de la méthode de régression d'arbre multiple nous avons défini pour chaque période d'années homogène des strates spatio-temporelles pour analyser les grandes tendances des déplacements spatio-temporels des senneurs.

(4) à partir d'une approche de patron de points (« spatial point pattern analysis ») nous avons décrit les changements dans la distribution spatiale de la flotte.

A partir de l'analyse bayésienne, on a mis en évidence que la série chronologique de chaque indicateur se subdivise en trois périodes de temps homogènes (i.e. deux changements soudains ont été trouvés pour l'ensemble de la période étudiée). En ce qui concerne le nombre de calées sur bancs libres, la 1ere année de changement (1988) correspond bien à l'introduction de dispositifs liés à la recherche de bancs libres (le sonar scanning 360° et le radar oiseaux de 30 kW de puissance) et la seconde (2002) est concomitante avec la généralisation de l'utilisation des courantomètres (il faut noter que quelques bateaux se sont équipés de deux sonars et de cartes satellites entre 2000 et 2003). Pour les prises de juvéniles sur DCP, les années de changement : 1991 et 1997, correspondent respectivement à l'introduction et au développement de la pêche sur DCP, bien que l'amélioration de ces dispositifs s'est poursuivie depuis son introduction jusqu'à nos jours et à la mise en œuvre du moratoire sur la pêche sur DCP.

Les strates spatio-temporelles (trois strates au total) pour le nombre de calées sur banc libre n'ont pas changé au cours des trois périodes d'années homogènes, alors que l'intensité des calées par strate a montré des changements (Figure 2.4). Par rapport aux captures de juvéniles sur DCP, il est apparu des changements des zones et saisons de pêche plus prononcés. Pendant la première (1981-1991) et la deuxième période (1992-1996), on observe deux strates spatio-temporelles, mais au cours de la deuxième période on assiste à une extension des zones de pêche vers l'ouest, ainsi qu'une augmentation des prises de juvéniles sur DCP (Figure 2.5). A partir de la mise en place du moratoire sur DCP en 1997, quatre strates spatio-temporelles ont été observées, ainsi qu'une réduction des prises de juvéniles sur DCP.

Dans ce chapitre nous avons montré un effet direct de l'introduction de nouvelles technologies sur l'efficacité de pêche pour chaque stratégie de pêche, et en plus un effet indirect en permettant de nouvelles tactiques spatio-temporelles pour le mode de pêche sur DCP.

C.1 Effets des fermetures spatio-temporelles sur la dynamique des flottilles de senneurs européens

Dans le troisième chapitre nous avons étudié les effets de la mise en place de mesures de régulation à la fois dans l'Atlantique et dans le Pacifique. La première section de ce chapitre correspond aux fermetures spatio-temporelles mises en place dans l'Océan Atlantique Est. En raison des augmentations des prises de patudo et en particulier de juvéniles associés à l'introduction massive de DCP, la Commission Internationale pour la Conservation des Thonidés de l'Atlantique (CICTA), dans le cadre du Programme d'Année Thon obèse (BETYP), a demandé des analyses pour déterminer des zones et des saisons de pêche visant à protéger les juvéniles de cette espèce. Dans ce contexte, les armateurs Français et Espagnols ont proposé en 1997 la mise en place d'une fermeture spatio-temporelle interdisant toutes les activités de pêche sur DCP pendant trois mois (novembre-janvier) dans une grande partie du Golfe de Guinée (Figure 1.9). Ce moratoire a été adopté et étendu pour toutes les flottes de senneurs par la CICTA en 1999. En 2004, la CICTA a adopté la recommandation [04-01] « Programme de conservation et de gestion pluriannuel pour le thon obèse » avec l'objectif de conservation et de gestion du stock de patudo. Cette recommandation a été mise en place en 2005 et a consisté en une réduction de la taille de la zone initiale adoptée lors du moratoire sur DCP ainsi que de la période (i.e. seulement novembre). Contrairement aux recommandations [98-01] et [99-01] qui ont interdit la pêche sur DCP, la recommandation [04-01] a interdit par contre toute capture de thonidés par les engins de pêche de surface. Dans ce contexte, l'objectif de cette section a été d'évaluer les effets de ces fermetures spatio-temporelles sur le comportement de la flotte de senneurs européens à l'aide de plusieurs indicateurs de pêche.

Nous avons utilisé des données de livres de bord correspondant à des senneurs français, espagnols ou associés à ces deux flottilles. Pour analyser l'activité de pêche de la flotte de senneurs européens et pour évaluer si la dynamique de la flotte a changé comme une conséquence de ces deux mesures de gestion, nous avons utilisé un ensemble d'indicateurs sur une base mensuelle : le nombre de jours avec capture, le nombre de carrés de 1° degré avec capture (tous deux représentant les succès de la flotte en fonction de la capture indépendamment de la méthode de pêche utilisée), et le temps de pêche représentant le temps passé par la flotte dans la zone. Le nombre de calées sur bancs libres a été utilisé pour détecter une éventuelle augmentation dans l'effort associé à cette méthode de pêche comme conséquence du moratoire sur DCP. Le nombre de calées sur DCP a été choisi pour représenter l'effet direct du moratoire sur DCP. Finalement nous avons calculé les captures associées à chaque méthode de pêche ainsi que les prises de juvéniles sur DCP.

L'approche *Before-After Control-Impact* (BACI) a été utilisée pour évaluer les effets de ces deux mesures de gestion. Cette approche permet (1) d'évaluer si un impact a modifié l'environnement, (2) de déterminer quelles composantes sont affectées et (3) d'estimer l'amplitude des effets (Smith 2002). En théorie cette méthode nécessite d'avoir des données avant et après l'impact et il est recommandé d'avoir une zone de contrôle pour permettre la comparaison avec la zone affectée. Cependant, dans cette étude nous n'avons pas choisi de zone de contrôle car la réallocation de l'effort de pêche en dehors de la zone où les mesures de gestion sont en vigueur peut affecter la zone en accès libre. Dans le cas du moratoire sur DCP nous avons défini deux périodes : avant (1995-1997) et après la mise en place (1997-2005). Comme conséquence, l'analyse BACI a été effectuée à l'intérieur et à l'extérieur de la zone réglementée. Par rapport à la fermeture totale aux captures de surface les périodes avant et après ont été fixées respectivement à 2000-2004 et 2005-2008. Dans ce dernier cas, l'analyse BACI a été effectuée uniquement à l'extérieur de la zone fermée i.e., pas de pêche et donc pas d'information à l'intérieur).

Les résultats ont montré qu'avant le moratoire sur DCP toutes les activités de pêche ont eu lieu principalement à l'intérieur de la zone. Une fois que le moratoire a été mis en place, une réduction de la pêche a été observée à l'intérieur de la zone sauf pour les activités associées à la pêche sur bancs libres, qui est restée identique à ce qui a été observé avant le moratoire. Les activités sur DCP ont augmenté à l'extérieur de la zone protégée ainsi que des captures associées à cette méthode de pêche. Il convient de souligner que les captures de juvéniles ont diminué à l'intérieur et à l'extérieur de la zone de moratoire sur DCP par rapport à avant la mise en place de cette régulation. Malgré cette réduction des activités de pêche à l'intérieur de la zone protégée, plusieurs activités sur DCP ont été observées à l'intérieur de la zone pendant les dernières années de ce moratoire, en particulier par la flotte de senneurs Ghanéenne-Coréenne. En raison de ces activités illégales la fermeture de la zone Picolo à la pêche de surface a été mise en place à partir de 2005. Cette nouvelle réglementation a entraîné une augmentation des activités de pêche à l'extérieur de la zone fermée sauf pour les activités sur DCP. Néanmoins, cette augmentation n'atteint pas le même niveau observé avant la mise en place du moratoire sur DCP et les captures de juvéniles ont augmenté malgré la mise en place de la fermeture.

Cette section a montré les différents effets des régulations spatiales sur la flotte de senneurs européens et met en évidence l'importance de prendre en compte les réponses des pêcheurs pour faire face à ce type de mesures de gestion.

C.2 Effets de la fermeture d'une saison de pêche sur la flotte de senneurs mexicains dans l'Océan Pacifique Est

Dans cette section du troisième chapitre, nous avons évalué les effets d'un arrêt de la saison de pêche sur la dynamique de la flotte de senneurs mexicains. Bien que les fermetures de saisons de pêche soient également utilisées par les gestionnaires de pêche afin de contrôler l'effort de pêche, ce type de mesure ne réduit pas en général l'effort de pêche, car les flottes peuvent accroître leur efficacité et leur capacité de pêche afin de maintenir les niveaux de capture (Branch et al. 2006; Fulton et al. 2011). Dans l'Océan Pacifique Est, la Commission Interaméricaine du Thon Tropical (IATTC) a traditionnellement utilisé les quotas de capture mis en place pour protéger l'albacore et le patudo à cause de l'augmentation de la taille de la flotte. En 2002, l'IATTC a reconnu que la production potentielle, et en particulier le recrutement, pouvaient être affectés par cet effort de pêche excessif et, en conséquence, l'IATTC a mis en place une limitation des captures de la pêche à la senne et a fermé une saison à la pêche (du 1er décembre au 31 décembre). Les années suivantes, cette mesure de gestion a subi quelques modifications mais la période de fermeture a toujours été la même. Il faut rappeler que dans le Pacifique tropical Est plusieurs mesures de gestion ont été mises en place ; par exemple, le moratoire sur la pêche des dauphins mis en place au début des années 1990 et la mise en place récemment d'une fermeture spatio-temporelle interdisant la pêche sur DCP. Cependant, nous ne disposons pas de données précédant la mise en place du moratoire sur les dauphins et comme la flotte mexicaine pêche sur ces espèces, la fermeture spatio-temporelle n'affecte pas la dynamique des senneurs mexicains. Pour ces raisons nous nous sommes limités à l'étude des effets de la fermeture de la saison de pêche sur les senneurs mexicains.

Nous avons supposé que la mise en place de cette mesure de gestion pourrait être une incitation pour les pêcheurs à être plus efficace. Pour cette raison nous avons décidé d'utiliser le nombre de jours par trimestre passés à quai, considérant que les pêcheurs pouvaient contrôler cet indicateur en accélérant le débarquement et/ou l'avitaillement rapide des fournitures pour la marée suivante. Pour évaluer un éventuel effet supplémentaire sur les principaux modes de pêche (i.e., la pêche sur dauphins et la pêche sur banc libre) nous avons calculé le nombre de mensuel de calées sur dauphins ainsi que sur banc libre, ainsi que les captures associées. Ces indicateurs ont été estimés en tenant compte de la capacité de charge du bateau (< 1000 t, ≥1000 t). Pour comparer les périodes : avant (1992-2001) et après (2002-2008) la mise en place de l'arrêt de pêche, nous avons utilisé des données d'observateurs avec une couverture de 50% sur l'ensemble des marées. Les comparaisons faites à l'aide du test Wilcoxon-Mann-Whitney ont été effectuées par paires de trimestres (i.e., avant/après). Dans le cas des autres indicateurs nous avons pris en compte la variabilité du climat en utilisant comme covariable la température de surface dans les régions océanographiques Niño3, Niño1+2 ou l'index d'oscillation australe (SOI). Dans le modèle linéaire généralisé, en plus du facteur avant et après, nous avons considéré la taille de bateau pour des raisons de préférence de pêche (i.e., les petits navires pêchent plus proches de la côte et normalement sur banc libre, tandis que les grands navires pêchent en haut mer et plutôt sur dauphins).

Les résultats ont montré que les senneurs mexicains ont réduit le nombre de jours inactifs passés à quai pour faire face à la mise en place de la fermeture de saison. En ce qui concerne la pêche sur dauphins, l'analyse a montré que la capture associée à cette méthode de pêche est resté au même niveau qu'avant la mise en place de la régulation, tandis qu'une augmentation du nombre de calées a été observée principalement sur les grands navires (≥1000 t). Le nombre de calées sur bancs libres n'a par contre pas été affecté par la taille des navires, tandis qu'une diminution a été observée après la mise en place de la fermeture de la saison de pêche et en conséquence une diminution dans les captures associées à cette méthode de pêche.

Cette section a montré comment la flotte mexicaine en réaction à la mise en place d'une fermeture de saison de pêche a réduit les temps de débarquement à quai afin de maintenir le même niveau de capture.

D. Conséquences des changements dans la technologie et les stratégies de pêche sur les thons non commerciaux et sur la faune associée

En plus de la viabilité à long terme des stocks de pêche, la gestion et l'atténuation des prises accessoires est aujourd'hui le problème le plus important auquel est confrontée la pêche industrielle. La mitigation des prises accessoires est devenue une préoccupation majeure pour les organismes de conservation (à la fois gouvernementaux et non gouvernementaux) et le public en général. Les groupes d'espèces comme les élasmobranches, les mammifères marins, les oiseaux marins et les tortues sont particulièrement vulnérables à la surexploitation et peuvent diminuer rapidement sur de courtes échelles temporelles. Dans ce contexte, le comportement du pêcheur et la dynamique de la flotte sont directement impliqués dans le niveau de prises accessoires résultant d'une large gamme de stratégies de pêche. Par exemple, l'effort de pêche est normalement alloué à des zones ou des saisons dans lesquelles les espèces cibles sont concentrées et peuvent être associées avec des espèces non ciblées par les pêcheurs. En Afrique de l'Ouest, le marché local d'Abidjan (Côte d'Ivoire) pour le « faux-poissons » (certaines espèces accessoires à forte valeur commerciale) risque de ne pas encourager les pêcheurs à éviter les prises accessoires (Romagny et al. 2000). Le ratio global des prises accessoires par rapport à la capture totale estimée pour la pêche à la senne des thons tropicaux reste toutefois faible (7.5%) et sans commune mesure avec d'autres pêcheries, par exemple dix fois plus faible que la pêche au chalut ou six fois plus faible que la pêche thonière à la palangre (Kelleher 2005). Cependant, dans la pêche à la senne malgré leur niveau limité les prises accessoires sont plus importantes sur DCP que sur bancs libres, pourraient capturer des espèces vulnérables.

Dans ce contexte, l'objectif de ce quatrième chapitre a été d'étudier les effets des modes de pêche de la flotte de senneurs européens, ainsi que les effets potentiels des nouvelles technologies ou des changements dans les stratégies de pêche sur les groupes d'espèces associées aux captures de thon. Pour cela nous avons utilisé des données provenant des programmes d'observateurs menés sur deux périodes historiques de la pêcherie différentes pour (1) étudier la variabilité temporelle de la composition spécifique des prises accessoires par mode de pêche (la composition spécifique des prises accessoires par strate temporelle obtenue dans le chapitre 2 est également décrite), (2) estimer la richesse spécifique des prises accessoires par mode de pêche ainsi que le nombre d'espèces accessoires pouvant potentiellement être pris. Cette analyse a été complétée (3) par une description de la distribution spatiale d'espèces accessoires figurant dans la Liste Rouge des Espèces Menacées de l'Union Internationale pour la Conservation de la Nature (IUCN), et enfin en réalisant (4) une analyse descriptive des calées effectuées sur les baleines et sur les requins baleines ; espèces importantes pour l'écosystème épipélagique, mais non considérées comme prises accessoires car étant des indices de détection visuels des bancs de thons mais n'étant pas remontés à bord.

Le premier programme d'observateurs (BETYP) a été effectué de la mi-1997 à mi-1999, avec un taux de couverture des marées de 8.7%. Les données du deuxième programme d'observateurs (Data Collection Framework, DCF) correspondent à la période 2005-2008, avec un taux de couverture de 3.8%. En raison de contraintes au cours de la calée certaines tâches associées aux prises accessoires ont été difficiles à accomplir pour les observateurs à bord. Pour ces raisons et en fonction des objectifs, les analyses ont été effectuées 1) au niveau des groupes taxonomiques d'espèces (thonidés mineurs, istiophoridés, requins, raies, tortues et autres téléostéens) et 2) sur la base du critère d'absence/présence au lieu du nombre d'individus. L'information liée aux observations de baleines et de requins baleines provient par contre des livres de bord.

L'analyse des changements sur la composition des espèces entre les deux périodes de temps a été effectuée en utilisant un test sur l'homogénéité des dispersions multivariées basé sur des matrices de dissimilarité (PERMEDIST; Anderson 2006). Nous avons choisi la distance euclidienne comme mesure de dissimilarité sur des matrices d'absence/présence dans lesquelles les colonnes correspondent aux espèces et les lignes aux unités d'échantillonnage en fournissant une résolution idéale pour mesurer les changements dans les communautés où de nombreuses espèces sont rares. Pour décrire la composition des espèces pour les strates temporelle établies lors des analyses réalisées au Chapitre 2, nous avons utilisé les occurrences de chaque groupe d'espèces dans une calée, sur DCP ou sur banc libre. Nous avons également calculé la probabilité d'occurrence de chaque groupe d'espèces définie comme le ratio entre le nombre de calées dans lesquelles un groupe d'espèces a été observé et le total de calées observées par strate.

La richesse spécifique, réalisée à travers des courbes de raréfaction, a été utilisée pour comparer les assemblages associés à chaque mode de pêche entre les deux périodes de temps. Cette méthode prend en compte l'hétérogénéité de l'échantillon et utilise les occurrences des espèces. Quand aucun autre taxon n'est ajouté, la courbe atteint une asymptote, cependant, l'asymptote n'est pas toujours atteinte. Dans ce travail, l'estimation de l'asymptote peut donner une idée du nombre d'espèces qui ne sont pas reportées ou qui peuvent potentiellement être capturées par les senneurs. Pour calculer ces asymptotes nous avons utilisé des indicateurs non-paramétriques de présence/absence de la richesse : Chao2, Jackkinfe1, Jackknife2 et Bootstrap (voir le Table 4.1 pour plus de détails), qui ont certains avantages sur les méthodes paramétriques (Colwell & Coddington 1994).

Les résultats du test PERMDIST indiquent que la composition spécifique n'a pas changé entre les deux périodes considérées, sauf pour les requins capturés sur DCP et peut être pour les raies capturées sur banc libre. On constate que la diversité d'espèces associées aux DCP est systématiquement supérieure à celle observée sur bancs libres. Dans les strates temporelles définies dans le Chapitre 2, le groupe « autres téléostéens » a présenté la plus forte probabilité d'occurrence. Au contraire, dans les calées sur bancs libres, ce sont les istiophoridés qui ont présenté la plus forte probabilité d'occurrence, suivis par les autres téléostéens.

En ce qui concerne la richesse spécifique, les deux modes de pêche présentent le même nombre d'espèces reportées (57 espèces sur DCP et 56 espèces sur bancs libres). Cependant, l'estimation des asymptotes indique que le nombre d'espèces pouvant être potentiellement capturé sur DCP est de 87 espèces, tandis qu'il n'est que de 66 espèces pour les bancs libres. En général les courbes de raréfaction pour les DCP croissent plus vite que celles pour des bancs libres, ce qui confirme que la diversité spécifique des prises accessoires sur DCP est plus grande que celle sur bancs libres.

Parmi les espèces reportées dans la liste de l'IUCN comme menacées, aucune n'apparaît très souvent, hormis le makaire bleu (*Makaira nigricans*) qui est considéré vulnérable et qui est capturé principalement sur DCP. Les autres espèces le plus souvent capturées sont le requin soyeux (*Carcharhinus falciformis*) capturé sur DCP, et le voilier de l'Atlantique (*Istiophorus albicans*) capturé particulièrement sur bancs libres. Cependant, aucune de ces espèces n'est considérée comme menacée dans la liste de l'IUCN (voir le Table 4.5 pour plus de détails sur les espèces menacées).

Dans les études sur les stocks de thons les calées sur baleines et les calées sur requins baleines sont considérées respectivement comme calées sur bancs libres ou sur DCP, en raison de la composition spécifique et des tailles des thons capturés sous ces deux modes de pêche. En raison de cette association entre grands types de calées, nous avons estimé le ratio annuel des calées sur baleine par rapport au nombre total de calées sur bancs libres. Ce ratio a été également calculé pour les requins baleines par rapport aux calées de type DCP. Ces séries annuelles n'ont pas montré une tendance nette mais une grande variabilité au cours de temps. Il est à noter que les deux séries annuelles n'ont jamais dépassé les 15% du total de calées sur DCP ou bancs libres et que d'autre part, le plus grand nombre de calées sur baleines et sur requins baleines a été enregistré pendant le deuxième et le troisième trimestre particulièrement dans la zone de Cap Lopez, très proche du Gabon.

Ce dernier chapitre a mis en évidence encore une fois l'importance de prendre en compte le comportement des pêcheurs, car selon le type de stratégie développé les niveaux atteints par les prises accessoires seront différents. Dans ce contexte, la pêche sur DCP a reçu plus d'attention des gestionnaires en raison de la quantité de prises accessoires observées ou de la présence d'espèces jugées vulnérables et la CICTA a pris des mesures pour réduire ces prises accessoires.

E. Conclusions et perspectives

Cette étude met en évidence l'importance de prendre en compte la dynamique de la flotte par rapport 1) à l'estimation des effets de l'introduction de nouvelles technologies sur les stratégies et tactiques de pêche développées par les senneurs ainsi que sur l'évolution de la capturabilité au cours des années, 2) à l'étude des réponses adaptatives des flottes faisant face à la mise en place de mesures de gestion et 3) à la description des effets des stratégies de pêche (i.e., une combinaison de mode de pêche, de saison et de zones) sur la diversité des prises accessoires. Une limitation toutefois en terme de généralisation des résultats est qu'en raison de contraintes liées à la disponibilité des données, la plupart des analyses ont été effectuées que sur la flotte de senneurs européens.

La préoccupation croissante sur le déclin des stocks halieutiques a conduit à la mise en place de mesures de gestion afin d'éviter la surpêche. Certaines de ces tentatives ont porté sur le contrôle de l'effort de pêche. Toutefois, contrôler l'effort de pêche ne signifie pas nécessairement que le comportement des pêcheurs et la dynamique de la flotte sont pris en compte. Par conséquent, les réponses imprévues des pêcheurs ont conduit à des échecs dans la réalisation des objectifs de conservation des stocks, et en particulier de les maintenir à des niveaux de rendements soutenables biologiquement et économiquement. Les pêcheries de thons tropicaux sont difficiles à gérer en raison de leur caractère hautement migratoire et de la nature différente des engins qui les exploitent. En raison de l'étendue de l'Océan Atlantique et de l'Océan Pacifique, la réalisation d'études pour obtenir des données indépendantes de la pêche est difficile et couteuse. Par conséquent, les données disponibles dépendront toujours en grande partie des pêcheurs (i.e., captures commerciales) et tout changement dans la dynamique de la flotte modifiera la relation entre les taux de capture et l'abondance (i.e., la capturabilité), qui est la base pour l'évaluation de ces stocks et des mesures de gestion qui en résulte.

L'investissement dans la technologie de pêche se fait de manière continue au cours des ans pour accroître les bénéfices ou pour réduire les coûts opérationnels. L'approche utilisée concernant l'introduction de technologie de pêche chez les senneurs français a permis l'observation d'effets directs sur les stratégies de pêche en augmentant la puissance de pêche, et des effets indirects modifiant les choix saisonniers des zones de pêche (i.e., les tactiques). Ces résultats mettent en évidence l'importance de surveiller le taux d'investissement dans la pêcherie. Nous sommes conscients que ce type d'analyse devrait être effectué sur d'autres flottes de senneurs qui peuvent avoir des pratiques de pêche différentes, et donc vraisemblablement des technologies distinctes introduites a des dates différentes. Il serait important que chaque pays ou les ORGP thonières comme la CICTA encouragent l'industrie de la pêche à contribuer aux recherches scientifiques en fournissant des informations concernant les investissements technologique introduits au cours des ans. Dans ce sens, la coopération étroite avec l'industrie de la pêche thonière française, comme l'association ORTHONGEL et l'armement SAUPIQUET pour accéder à ces informations importantes a été remarquable.

L'augmentation des captures de thons immatures et juvéniles au début des années 1990 a incité la CICTA et l'IATTC à mettre en place des mesures de gestion visant à réduire ces effets. Encore une fois, la participation de l'industrie de la pêche dans l'Océan Atlantique a permis d'établir le moratoire volontaire sur les DCP. Par conséquent, une diminution des captures sur DCP a été observée, mais le suivi et la normalisation de toutes les flottes opérant dans cet océan ont été difficiles, menant à des activités de pêche illégales, non réglementées et non déclarées. La réallocation de l'effort de pêche est importante à considérer lors de la définition de fermetures spatio-temporelles car il pourrait conduire à une augmentation de la pression de pêche à l'extérieur de la zone réglementée sur des secteurs limitrophes ou éventuellement sur des secteurs plus éloignés mais riches en espèces vulnérables. D'autre part, la flotte mexicaine dans l'Océan Pacifique Est a fait face à la restriction de la saison de pêche en réduisant le temps passé au port pour assurer plus de temps en mer et maintenir ainsi le niveau de captures observées avant la mise en place de la mesure de gestion. Les régulations spatiales et/ou temporelles doivent être accompagnées d'autres outils de gestion pour éviter d'aggraver la pression de pêche à l'extérieur de la zone fermée ou avant la fermeture de la saison. En ce sens, des analyses de simulation devraient être faites pour évaluer les réponses possibles des pêcheurs avant la mise en place de mesures de gestion. Nous pensons que les indicateurs utilisés dans cette thèse pourraient être utilisés comme données d'entrée pour effectuer de telles simulations.

L'utilisation croissante et continue des DCP a suscité des préoccupations quant aux effets sur l'écosystème épipélagique, devenant ainsi un problème de gestion. Il faut toutefois garder à l'esprit que les prises accessoires provenant des senneurs sont plus faibles que dans beaucoup d'autres pêcheries (e.g. palangriers, chalutiers, filets maillants) et qu'elles sont parfois utilisées comme des sous-produits pour les marchés locaux. Cependant, les prises accessoires générées par la pêche à la senne contribuent à la déplétion des populations de prédateurs supérieurs, pouvant entraîner des problèmes au niveau des réseaux trophiques. En ce sens, la participation des pêcheurs pour réduire les prises accessoires est cruciale afin (1) d'éviter des taux élevés de prises accessoires en prenant de bonnes décisions avant d'effectuer une calée, et (2) de savoir ce qu'il faut faire avec les prises accessoires une fois à bord. Pour aller vers une mitigation effective des espèces accessoires vulnérables la participation des techniciens de la pêche est également importante. Cependant, pour les espèces associées pour lesquelles il n'y a pas d'évidence de surexploitation la proposition de certains auteurs (e.g. Zhou 2008; Garcia et al. 2012) sur la « pêche équilibrée » semble réaliste dans un contexte d'utilisation de ces produits comme à Abidjan et devrait être considérée par les Commissions thonières internationales dans une approche plus écosystémique de la gestion des pêches.

Les outils statistiques utilisés dans cette thèse ont permis d'étudier la dynamique de la flotte dans certains aspects. Toutefois, d'autres outils statistiques peuvent être utilisés pour analyser le comportement de pêcheurs, par exemple, les modèles à choix discrets ou « Random Utility Models », pour analyser les choix décisionnels ou encore les réseaux neuronaux artificiels pour simuler la prise de décision pour changer, ou non, de zone de pêche ainsi qu'analyser l'effet du partage d'informations entre les pêcheurs sur leur efficacité. Nonobstant, cette thèse est une étape vers l'intégration de la dynamique des flottilles pour améliorer la gestion de la pêche à la senne.

General introduction

The main components in a fishery are both fish populations in their ecosystems and humans pursuing and capturing the fish (Branch et al. 2006). How they interact, is a key issue in fisheries management and because a fishery system is a sort of predator-prey system, it is equally relevant to understand and monitor the basic processes that determine the dynamics of the predator (Hilborn and Walters 1992).

During the fishing process each fisherman may choose different options about resource use, but limitations imposed by environmental or market variability may influence the way fishermen exploit their resources (Salas and Gaertner 2004). As a consequence fishermen develop and implement fishing strategies and short-term tactics in response to the constraints they encounter and their intended objectives given particular human, social, cultural and economic contexts (Laloë and Samba 1991; Pelletier and Ferraris 2000; Salas and Gaertner op. cit.). Management objectives refer traditionally to protect the ecosystem, but the fleet dynamics is rarely accounted for. However, fishing being a human activity, the societal goal for stakeholders is maintaining healthy fish stocks to ensure sustainable fisheries, i.e. to sustain the jobs, income, and food that flow from fishing activity (Branch et al. 2006).

It is admitted that during the discovery and growth phase of fisheries the primary dynamic is the entry of participants, the expansion of fishing capacity and the exploration of new fishing grounds. Management measures are usually minimal during this development phase. However, during the growth phase conditions that are set can encourage subsequent overcapitalization and economic decline (Branch et al. 2006). In established/mature fisheries, management tends to become more intrusive. Limited entry is usually introduced and stock assessments become critical. Management measures have been implemented to avoid undesirable effects on tropical tuna species but they have not taken into account the fleet dynamics yet. Some management measures have tried to control fishing effort by restricting season-length or fishing areas. Traditionally input data in stock assessment come from (1) fisheries, for instance, commercial catch per unit effort (CPUE), catch length frequencies; and (2) fisheries-independent data (this is not the case for tunas), generally obtained from standardized vessel or scientific acoustic surveys. Commercial data change as fisheries develop, because fishermen may invest in fishing gear and equipment, expand offshore, start fishing in different areas, or target different components of the population (Branch et al. 2006). As a consequence, ignoring fishermen behavior in fishery models may result in a wrong perception of the dynamics of the fishery, in erroneous stock assessments diagnosis, and finally in inappropriate management advices (Pelletier and Ferraris 2000).

In the case of tropical tuna purse seine fisheries, due to the high mobile characteristic of these species, fish availability varies in space and time (Cayré et al. 1993; Lehodey et al. 1997). When environment conditions are adequate, adult tuna aggregate into schools that gather into large concentrations (Stretta 1993; Ravier et al. 2000; Fonteneau et al. 2008). Moreover, fishermen have to face environmental conditions that could limit their fishing activities. In this study two purse seine fleets are analyzed (1) the EU fleet operating in the eastern Atlantic Ocean and specifically the French fleet with respect to the introduction of new technology, and (2) the Mexican fleet fishing in the eastern Pacific Ocean. These purse seine fleets are exposed to different environmental conditions in each ocean. The Atlantic is characterized by a strong seasonality while in the Pacific the main feature is the interannual variability, largely influenced by El Niño-Southern Oscillation. Operating in these ocean-specific conditions, each fleet has also developed different fishing strategies: the French fleet fishes mainly on free-swimming schools and FADs, the Mexican fleet fishes mainly in dolphin-associated tuna schools.

According to Hilborn and Walters (1992) the dynamics of the fleets can be divided into four parts: (1) fishery investment, (2) spatio-temporal fishing effort allocation, (3) determinants of fishing power, and (4) determinants of discarding. By increasing the fishing power component of the catchability over the years (Arreguín-Sánchez 1996), investment and developments in fishing gear and practices generally modify the relationship between catch rates and abundance (Bishop 2006).

Fishery investment exists from the initiation of the fishery, usually with the entry of vessels from other fisheries or from vessel construction. However, in established/mature fisheries like tuna purse seine fisheries, the investment may be done to catch more fish and/or to improve the quality of landings (Kennelly and Broadhurst 2002) as well as to face management measures such as restrictions on season-length or vessel and gear restrictions (Branch et al. 2006).

The fishing effort allocation, as mentioned earlier, is influenced by the spatio-temporal distribution of the resources and the environmental conditions. It may be constrained by the distance from port (Sampson 1991) or costs associated with the distance between different fishing areas (Caddy and Carocci 1999). Management measures such as time-area closures will also modify it. However, vessels better equipped can explore new fishing grounds and expand the fishery.

The fishing power is related with how many fish is caught by fishermen. The catch of a vessel is determined by different factors (Hilborn and Walters 1992): what species to target, how often it captures, local abundances where the vessel operates, and the crew's skills relative to other vessels operating in the same area. Increased resulting fishing power is mainly due to technical improvement of the existing vessels, or improved fishing efficiencies of the new vessels (Fonteneau et al. 1999).

Some fishing methods and gears are more selective than others and the lack of selectivity results in catches of non-target species. In this manner, bycatch, discarding and high-grading may affect management in a variety of ways (Hall 1996; Kennelly and Broadhurst 2002; Branch et al. 2006). Discarding occurs in most fisheries, some undersized individuals are caught, others are the wrong species, and still others may be diseased or damaged (Hall et al. 2000). High-grading occurs in fisheries that have individual output controls, such as trip limits or individual quota systems, in which there is also a price differential between different sizes of fish and little effort is needed to catch fish to replace those discarded (Hall et al. 2000; Branch et al. 2006).

In such a context, the scope of the present study is to explore the fishing dynamics of the EU and the Mexican purse seine fleets which are among the most important tuna surface fleets in the regions which they operate and to attempt to highlight the internal (e.g. new fishing technology for the French fleet) or external factors (e.g. time-area regulations) which have impacted the spatial distribution of the fleets and the fishing practices.

The tuna purse seine fisheries in the eastern Atlantic Ocean and the eastern Pacific Ocean are described in Chapter 1. In order to better understand the context and the findings of this study, we first describe the development of the fisheries, and the main fishing modes. Then some biological characteristics of the main tuna caught are described, as well as some oceanic conditions. Finally tuna purse seine fisheries management is described.

In Chapter 2, the effects of the introduction of new technology on the fishing strategies and spatio-temporal tactics of the French purse seine are studied over the period 1981-2008. Since the relation between catch rates and abundance is modified by fishing gear and practices it is important to better understand the way in which technological investment affects fishing activities. We hypothesize that the new technology has not only improved the fishing efficiency in the long-term of the fleet but also the way fishermen exploit the different fishing grounds to which they have access. To assess this hypothesis a sequence of statistical methods is applied to two representative fishery indicators of the fishing strategies of the fleet. The analyses will allow evidencing the effects of the introduction of new technology at different temporal scales. It was not possible to perform the same analysis on the Mexican fleet because the main technological improvements were implemented in the 1980s, and unfortunately the data are available only since 1992.

In Chapter 3 the effects of management regulations on the fleet dynamics are evaluated. From the early 1990s an increase in bigeye tuna juveniles was observed due to the massive deployment of FADs in the eastern Atlantic Ocean. Therefore, the ICCAT established two spatio-temporal regulations: one banning FAD-fishing and then one prohibiting all type of surface fishing. We assume that the former increased free-swimming school fishing activities and reallocated the FAD-fishing activities, while the latter increased fishing activities outside the closed area compared to before its implementation. We use a set of fishery indicators related with the dynamics of the fleet to gauge the effects of the spatio-temporal regulations by means of the Before-After Control-Impact approach. In the eastern Pacific Ocean we explore the effects of another type of restriction based on a season-length regulation. Notice that in this region there have been some management regulations, but the moratorium on dolphins started in 1992 and in the data base there is not information prior to this year. In addition, a closed area established by the IATCC only applied to FAD-fishing, which does not affect the Mexican fleet which target tuna schools associated with dolphin herds. The closed season regulation was established to reduce fishing pressure on tunas due to a continuous fishing capacity growth. We suppose that the Mexican fleet faced this regulatory measure increasing the time spent at sea to compensate the closed season. We estimate some fishery indicators to ascertain this hypothesis, considering interannual climate variability and vessel size. The analyses are carried out using nonparametric statistical hypothesis test and generalized linear models.

Finally, in Chapter 4 the consequences of the fishing strategies on the bycatch are explored. Since tropical tunas use to associate with other species and on floating objects, bycatch has become an issue management. Within the framework of ecosystem-based fishery management, tropical tuna purse seine fisheries cannot be assessed only in terms of tuna catch due to their nature. We suppose that as a result of changes in fishing strategies, bycatch has been affected in terms of species composition affecting the epipelagic ecosystem. We compare species composition between two periods of years using observer data from the EU purse seine fleet by means of a dissimilarity-based test for homogeneity of multivariate dispersions. We estimate the species richness of both periods and through rarefaction species curves and nonparametric indicators we extrapolate the number of species potentially undetected or uncaught by fishing modes. Then we describe the impact over time of the purse seine fishery on bycatch and we analyze briefly the spatial and seasonal distribution of the sets exerted on two tuna-associated schools: sets on whales and on whale sharks. Such analysis was not possible to carry out in the eastern Pacific Ocean because Mexican purse seine fleet fishes mainly on dolphin-associated tuna schools and lesser extent on free-swimming schools. Moreover, dolphin mortality has remained stable along the data period.

Chapter 1

The purse seine tuna fishery in the eastern tropical Atlantic and Pacific oceans

1.1 Introduction

The total catch of tuna and tuna-like species was about 6.3 million t in 2008, which represented 7.9 % of the 79.5 million t of the global production of marine capture fisheries (FAO 2010). The main commercial tuna species (i.e., albacore, bigeye, bluefin -three species-, skipjack and yellowfin) contributed 4.2 million t. Skipjack, yellowfin and bigeye were the most productive tuna species (contributing about 57%, 27% and 10%, respectively). About 65% of the 3.97 million t of tropical tuna (yellowfin, skipjack and bigeye) catches was from the Pacific Ocean, followed by the Indian Ocean (26%) and then the Atlantic Ocean (9%).

Different fishing gears capture tropical tuna, but some differences are observed among these tuna fisheries: the longline fishery targets mainly large bigeye and yellowfin tuna, the pole-and-line (termed also bait boat) fishery targets mainly skipjack, followed by yellowfin and bigeye (Dakar, Canary, Azores), and the purse seine fishery targets yellowfin and skipjack. Historically, longline and pole-and-line used to be the major tuna fishing gears worldwide (over 80%), but these have rapidly declined in proportion (at only 10%) despite that catches have been slightly increased or stable (**Figure 1.1**; Miyake et al. 2010). Such a situation is due to the major development of purse seine catch since the beginning of the 1980s; the world purse seine catch has rapidly increased to nearly 3 million t (or 70% of world tuna catches).

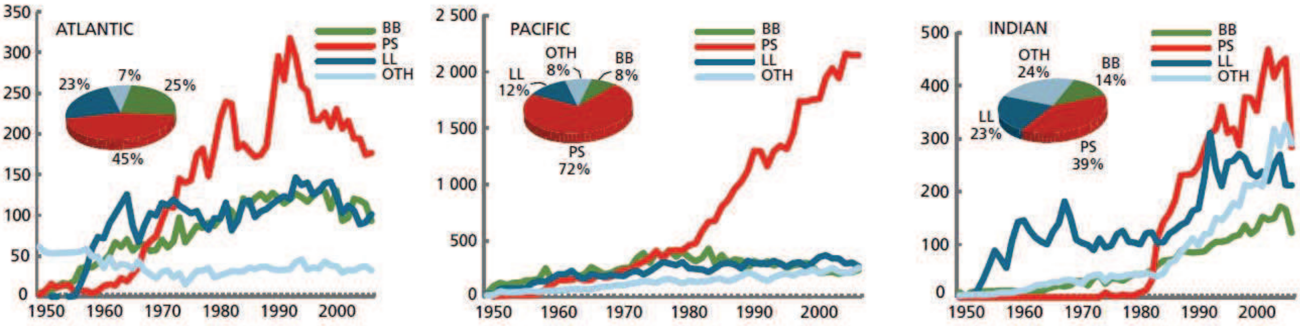

Figure 1.1 Tuna catch (thousand tons) by ocean and by gear (BB=Bait boat, PS=Purse seine, LL=Longline, OTH=other fishing gears) from 1950 to 2007. Pie chart is the average proportion by gear from 2001 to 2005. Source: Miyake et al. 2010.

Given the tunas' highly mobile nature and the significant size and global nature of the tuna fisheries, several regional fishery management organizations (RFMOs) have been established to manage these fisheries within a regional/ocean context: in 1949 the Inter-American Tropical Tuna Commission (IATTC) in the eastern Pacific Ocean (EPO); in 1969 the International Commission for the Conservation of AtlanticTunas (ICCAT) in the Atlantic Ocean and adjacent seas; in 1993 the Commission for the Conservation of Southern Bluefin Tuna (CCSBT) in all oceans in which southern bluefin tuna occurs; in 1996 the Indian Ocean Tuna Commission (IOTC) in the Indian Ocean; and recently in 2004 the Western and Central Pacific Fisheries Commission (WCPFC) in the western and central Pacific Ocean. Membership of the RFMOs is composed of both coastal nations and distant-water fishing nations. This chapter will describe the features of the purse seine fisheries in the eastern tropical Atlantic and the eastern tropical Pacific oceans, where are operating the Mexican and the French purse seiners, respectively whose the dynamics at sea are the core of this study.

1.2 Development of the purse seine tuna fishery

Purse seine tuna fishing is a relatively old technique. Immediately after the World War I many purse seine fishermen from Alaska and the Pacific Northwest entered the California fisheries. This technique was successfully adapted to the capture of yellowfin and skipjack tuna, but it was until after the World War II this fishery grew rapidly (Shimada and Schaefer 1956).

In the eastern tropical Atlantic, purse seine tuna fishing was introduced in the Gulf of Guinea in the early 1960s by vessels from the United States, Spain and France (Couliou 2001; Fonteneau et al. 1993). Several countries joined the first vessels operating in the eastern tropical Atlantic (e.g. Japan, Canada, Senegal and Côte d'Ivoire). At that time, vessels were of small carrying capacity (100 t) and equipped with a purse seine of 800 m long and 100 m depth. From the mid-1960s to the mid-1970s, when seiners started operating in the eastern tropical Atlantic, the catches were made in coastal waters off Western Africa, from 25°N latitude to 25°S latitude (**Figure 1.2**; Fonteneau et al. 1993). During this period, most of the purse seiners belonged to France, United States and Spain.

From the late 1970s to the early 1980s the purse seine fishery had an expansion as far as the Gulf of Guinea (**Figure 1.2**). This extension toward the open sea areas had the effect of increasing the catch of larger yellowfin than those that were caught until 1974 in the coastal zone. In this period, France and Spain were the main purse seine fleets. In the mid-1980s a combination of several factors (high CPUEs observed in the Indian Ocean, low Atlantic catches in 1984 due to the deepening of the thermocline, etc) resulted to a partial reallocation of the purse seiners fishing effort to the Indian Ocean.

In the early 1990s the fishery expanded beyond the Gulf of Guinea mainly due to the development of the fish aggregating devices (FADs) fishing method (**Figure 1.2**). Purse seine nominal fishing effort decreased in the early 2000s, and in the late 2000s some purse seiners returned from the Indian Ocean to the Atlantic Ocean due to piracy problems in Somalia. From the 1980s, European purse seiners (France, Spain and associated flags) compose the most important fleet in the surface tuna fishery in the eastern tropical Atlantic Ocean.

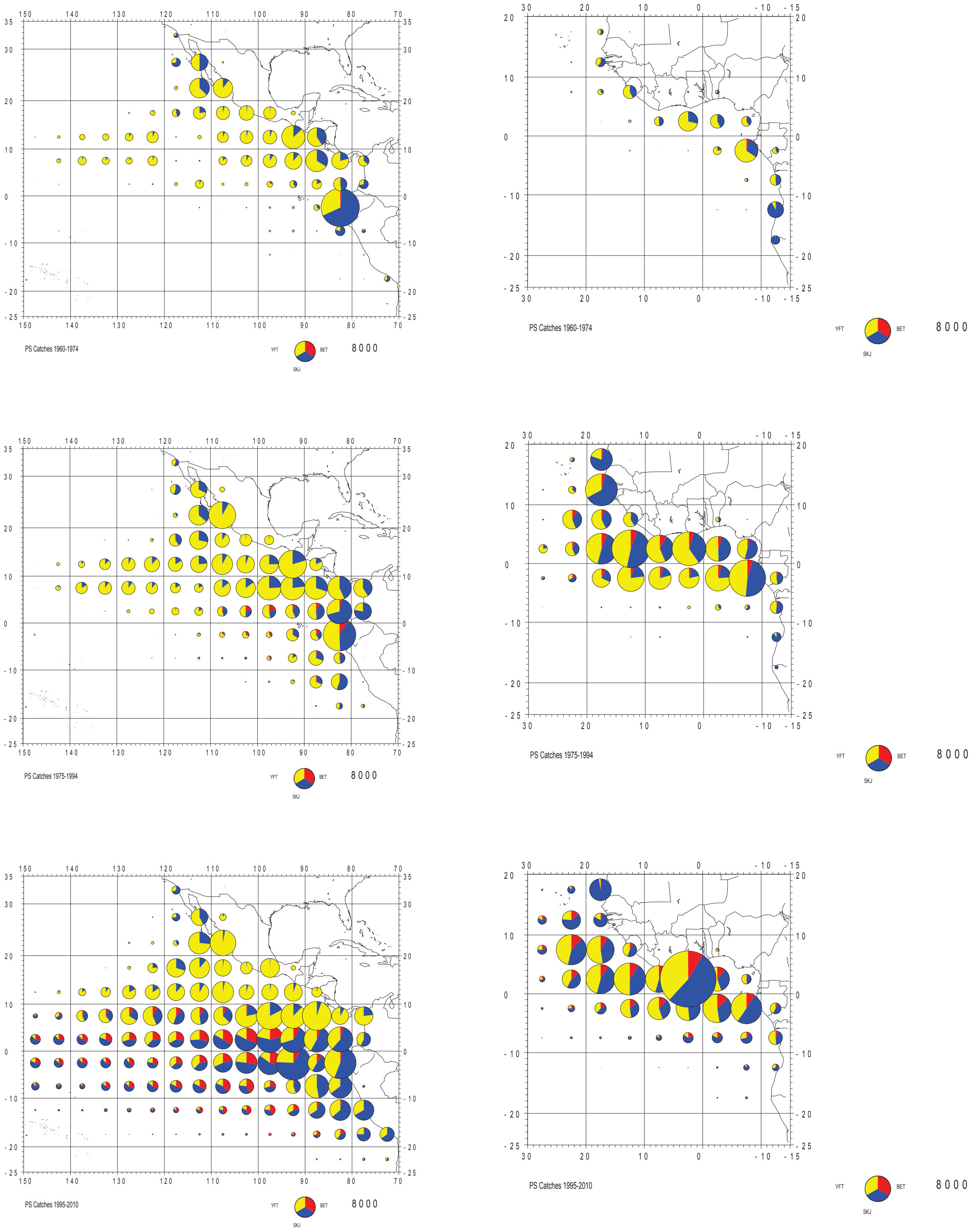

Figure 1.2 Annual average catches of the main tropical tuna (yellowfin, skipjack and bigeye) by purse seiners in the eastern Pacific and eastern Atlantic oceans, along three time periods (1960-1974, 1975-1994 and 1995-2010). Courtesy of A. Fonteneau.

In the EPO, prior to 1959 pole-and-line fleet dominated the tuna catches in the eastern tropical Pacific (Calkins 1963). Many of the seiners were engaged in other fisheries during the fall and early winter months and consequently most of the fishing effort for tuna occurred in the period February-August (Shimada and Schaefer 1956). The vessels were quite small, averaging approximately 120 t carrying capacity (Calkins 1963). During the period 1959-1961 most of the large bait boats were converted for purse seining and the existing purse seiner fleet was modernized. Fishing effort originaly confined to an area within a few hundred kilometers of the continent and near waters adjacent to islands such as the Revillagigedo, Galapagos, Cocos, Malpelo and Clipperton, began to expand offshore in the late 1963 (**Figure 1.2**). From this year to 1966 the numbers of 1-degree square visited ranged from 205 to 270. During 1967-1970 the offshore expansion of this fishery continued and the numbers of 1-degree squares explored exceeded 300. In the 1960s the purse seine fishing was well developed and the main countries in this fishery were the United States (US) and Ecuador. During this period the Mexican purse seine fleet started operate with 6 vessels (Calkins and Chatwin 1971).

During the 1970s the purse seine fishery was extended between the Commission's Yellowfin Regulatory Area (CYRA) boundary and the 150°W longitude (Calkins 1975; Orange and Calkins 1981). In the late 1970s, the expansion was southward of the fishing area between about 80°W and 110°W longitude (**Figure 1.2**). The fishery was expanded considerably from about 5 to 15°N latitude and between 110 and 120° W longitude (Orange and Calkins 1981). In the 1980s purse seiners were well extended between the CYRA boundary and the 150° W longitude. The most exploited areas were around 10°N latitude, the Mexican coast and the Gulf of Panama. During this period, Mexican purse seine fleet depicted a rapid development and became as important as the US and Ecuadorian fleets in terms of volume catch and carrying capacity (Ortega-García 1996).

In the early 1990s many US vessels left the EPO, with a consequent reduction in the fleet. However due to the participation of other countries in the fishery, the total carrying capacity has steadily increased since 1992, and was close to 210 000 m^3 in 2010. During this period, the FAD-fishing development was the cause of the expansion of the purse seine fishery along the equator, from the coast of Central America to the 150°W longitude (**Figure 1.2**; Lennert-Cody and Hall 2000). At the present time, Ecuador, Mexico and Venezuela have the main purse seine fleets operating in the EPO.

1.3 Purse seine fishing modes

Tuna schools are detected visually through sighting indices at the surface of the sea during daylight hours. Tropical tuna purse seine fishing in the world ocean is mainly made on free-swimming schools and floating objects drifting (**Figure 1.3**). However, in the EPO, tuna are frequently associated with herds of dolphins, mainly yellowfin tuna (**Figure 1.3**). Fishermen take advantage of this association and this fishing mode is of some importance in this region. In this section, it will be briefly described each of these fishing modes. For details about the setting process see Annex A1.

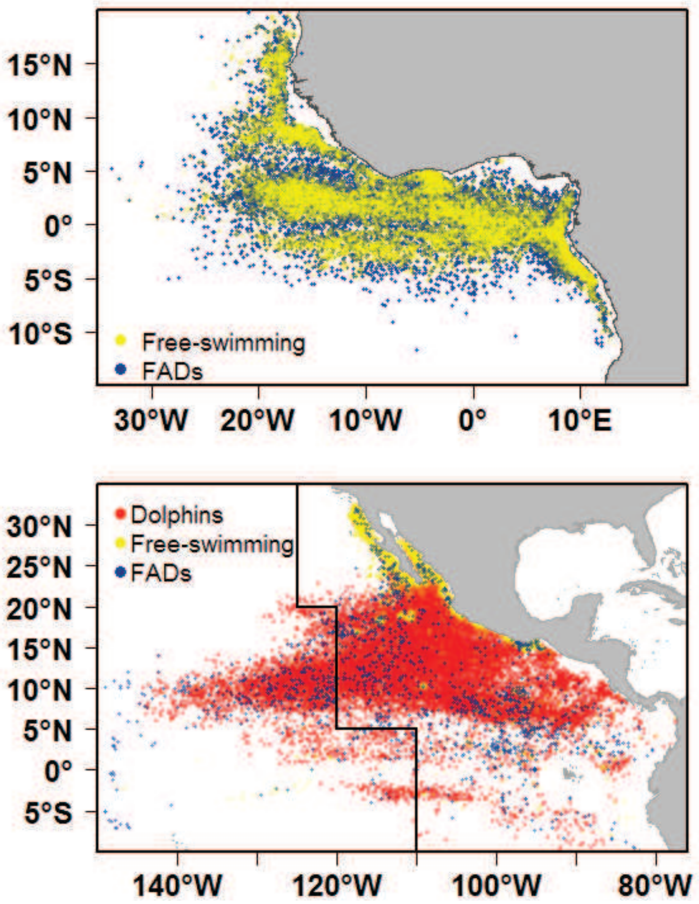

Figure 1.3 Spatial distribution of the French and Mexican tuna purse seine fleets in the eastern Atlantic and eastern Pacific oceans from 1981 to 2008 and from 1992 to 2008 respectively. It is shown the main fishing modes: Dolphin-associated school (red), Free-swimming school (blue) and FAD-fishing (yellow). For the Pacific Ocean the area between the coast and the straight lines corresponds to the Commission's Yellowfin Regulatory Area (CYRA).

1.3.1 Fishing on free-swimming schools

In this fishing mode, flock of birds, or when the water surface is disturbed by what appears to be a local breeze are the main sighting indices used to detect tuna schools. However, for the sake of simplicity, due to the fact that species composition and size of the fish are comparable to non-associated school, sets made on whales are considered as free-swimming school sets (Pallarés and Petit 1998). Fishing on free-swimming schools requires high time spent in the searching process, and depends in the skipper's skill.

In the eastern tropical Atlantic, fishing on free-swimming school used to be more important than fishing on floating objects (**Figure 1.3**). This technique usually captures large yellowfin tuna over 100 cm fork length (FL; >30 kg) throughout the eastern Atlantic Ocean but with a peak in January-March when spawners concentrations of yellowfin are found in the Gulf of Guinea. For a long time, some free-swimming schools of large skipjack was caught in waters off Senegal in May-June. However since 2005 there has been no renewal of fishing agreements with Senegal. It should be noted that mixed species free-swimming schools were reported before the development of FAD-fishing (Fonteneau 2000a).

In the EPO, since large yellowfin are mainly associated with dolphins, free-swimming schools are most associated with small yellowfin tuna of around 60 cm FL (< 5 kg) and with skipjack tuna. Fishing on free-swimming school is deployed mainly within the Exclusive Economic Zones (EEZs) of all countries of the region (**Figure 1.3**).

1.3.2 Fishing on natural floating objects and drifting fish aggregating devices (FADs)

Tropical tuna species are attracted to floating objects and consequently fishermen use this behavior to their advantage, capturing the tuna beneath the object. Tuna fishing on natural floating objects has been used by most purse seine fisheries since the early 1960s in coastal areas where they were abundant (Fonteneau et al. 2000b). In the Western and Central Pacific Ocean and Indian Ocean, the proportion of catches from floating objects has been relatively high (70 to 80%) even before the introduction of FADs (Fonteneau et al. 2000b; Miyake et al. 2010). This fishing mode target mainly skipjack tuna, and juveniles of yellowfin but also capture incidentally juveniles of bigeye tuna. Tuna also tend to associate with whale sharks, as well as sets on whales, species composition and size of the fish are comparable to logs associated school, thus, sets on this species are grouped with FADs sets (Pallarés and Petit 1998).

The origin of most of natural floating objects is the river runoff, and consequentely their occurrence at sea is related with the rainy seasons. However, since the introduction of drifting FAD-fishing by purse seine fisheries, this fishing mode has shown a massive development worldwide. FADs are usually made of bamboo poles, or panels of netting. As a result of the high catch rates associated with these FADs, they have been equipped with positioning and tracking devices. FADs are deployed throughout the year.

Based on observations on catch per set during the day hours (in general sets on FADs are most frequent at dawn than during the rest of the day), tunas would associate with drifting floating objects during night, and then would leave them early in the morning (Hall 1998), notwithstanding, the reasons of this fish aggregation are not well known (Castro et al. 2002). When the skippers find a floating object with tuna around it they assess the size of the school, visually or with the aid of electronic devices (e.g., echosounder), and then depending on the decision to set or not, the purse seine is deployed around the school. FADs are monitored by the boat that has “sown” them, using a range of location systems based on beacons that transmit radio signals or by satellite. FAD-fishing increased the encounter rates as well as the success on setting a school (FADs sets 96% vs. free-swimming schools 74%, respectively; Pianet et al. 2011), and decreased the costs related to searching process observed on free-swimming schools. Along this manuscript the acronym FAD will embrace both drifting natural (e.g. logs, palm branches) and anthropogenic floating objects such as man-made bamboo rafts equipped with radio-range beacons or satellite transmitters and scanning sonars.

In the eastern tropical Atlantic, natural logs have always been present from April to October near to the discharge of the Congo River in the region of Congo, Gabon and Equatorial Guinea (**Figure 1.4**). Then they drift along the African coast until the region off Liberia (Ariz et al. 1993). However, since the 1990s FADs are mainly deployed along the equator throughout the year (Ariz et al. 2000).

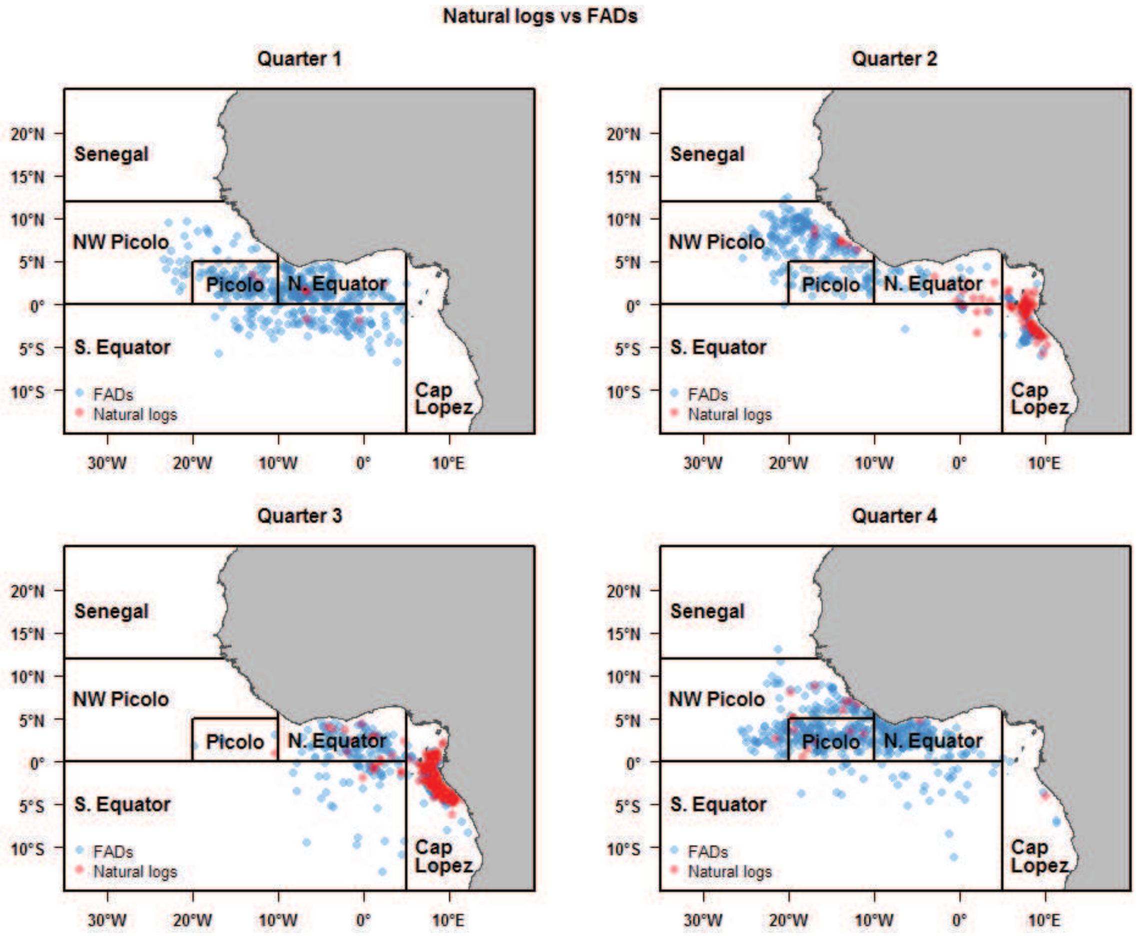

Figure 1.4 Quarterly spatial distribution of sets made by French purse seiners on FADs (blue) and natural logs (red) from 2005 to 2011.

In the EPO, the coasts of Colombia, northern Ecuador, Costa Rica, Panama, and the Guatemala-Mexico highland are areas of high annual precipitation (Hall et al. 1999). The greatest number of sets associated with floating objects and unassociated sets were made from the mid-1970s to the early 1980s (IATTC 2011c). During the 1980s, sets on natural floating objects occurred predominantly in the coastal and inshore waters of Central America. It was not usual log-fishing off western Mexico or the Baja California peninsula, where there are few rivers and forest. From the mid-1990s, FADs have been widely used and their relative importance has increased during this period while that of logs has decreased (IATTC 2011c).

In both oceans mixed species schools are caught, in which the main species is skipjack (over 45 cm FL), small yellowfin (between 45 and 60 cm FL), and bigeye tuna (from 40 to 65 cm FL) (**Figure 1.5**).

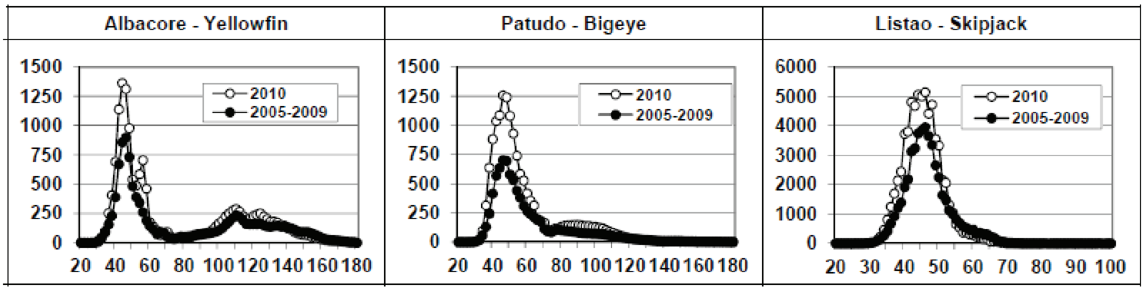

Figure 1.5 Length distribution of tropical tunas taken by EU purse seiners under FADs in 2010 (white dots) and the average from 2005 to 2009 (black dots). Source: Pianet et al. 2011.

1.3.3 Fishing on dolphins

In the EPO, by 1959, when the purse seine fleet expanded to areas off the coasts of southern Mexico and Central America, an increase in catches of large yellowfin tuna (over 100 cm FL) were observed associated with herds of spotted (*Stenella attenuata*) and spinner (*S. longirostris*) dolphins (Broadhead 1962), and in a minor level with the common dolphin (*Delphinus delphis*) and occasionaly with the striped dolphin (*S. coeruleoalba*; Hall 1998). This fishing mode has been deployed from the beginning of the purse seine fishery to nowadays. The tuna purse seine catches on dolphins are made mainly from the coast to around140° W longitude along and north and south of the 10°N latitude (**Figure 1.3**).

When the fishermen detect a herd of dolphins, of one or more of the species known to be associated with tunas, they attempt to confirm the presence of tuna either with the aid of the helicopter, or from the vessel (Hall 1998). When tunas are present they launch four or five speedboats that chase the dolphin herd, making a wide arc typically at a distance of 100-200 m to the side and behind the herd (Hall 1998). The dolphin-associated set usually lasts about 20 to 30 minutes, and when it finishes, the dolphin herd has slowed down, or stopped. During this process, part or the whole dolphin herd may evade the encirclement, or may be deliberately excluded from the encirclement area through the actions of the speedboats.

Because of natural factors (e.g., currents), equipment malfunctions, or lack of expertise or motivation of skippers and crews, many dolphins among the 400-500 individuals captured generally and normaly released when the net is pursued, have died incidentally during these fishing operations (Hall 1998). The incidental mortality of dolphins caused by this technique generated considerable controversy around its legal, economic, political and ecological aspects. As a consequence many purse seiners left the fishery or switched from fishing on dolphins to FAD-fishing with unexpected consequences in terms of mortality of many other organisms (Hall 1998).

1.4 Tropical tunas in the Atlantic and Pacific oceans

1.4.1 Biology of tropical tunas and status of the stocks

Tropical tuna (**Figure 1.6**) are among the top predators in the epipelagic marine ecosystem food web. Tuna have exceptional physiological and morphological features (Sharp 1978). All tunas are oviparous, multiple spawners and shed their gametes directly into the sea where sea surface temperature are warm. Tuna are constrained to some extent by the availability of oxygen (Prince and Goodyear 2006) and appropriate water temperatures, and these constraints depend on time of the day, season, stage of development, and reproductive status (Sund et al. 1981; Brill 1994; Block and Stevens 2001).

Figure 1.6 Main commercial tropical tuna species: yellowfin tuna (*Thunnus albacares*), skipjack (*Katsuwonus pelamis*) and bigeye tuna (*T. obesus*).

Thunnus albacores (Yellowfin tuna)

Yellowfin tuna has a cosmopolitan tropical and warm-temperate distribution. In the eastern Atlantic is known from the Azores to South Africa (Diouf and Amon-Kotias 1993) while in the eastern Pacific is distributed from Point Conception, California to San Antonio, Chile (Wild 1994). The common sizes range between 50 and 150 cm fork length with a maximum of 200 cm. When the concentration of oxygen is not the limiting factor, yellowfin distribution in the column water is set by the strength of the thermocline (Holland et al. 1990). The water temperature preferences of this species range from 20.5° to 25.8 °C, but yellowfin tolerates until 16.4 °C (Boyce et al. 2008). It spends more than 90% of its time in waters with a uniform temperature of around 22º C (Brill et al. 1999). Yellowfin adults and juveniles spend most of their time in the surface layer, above 100 m (Brill et al. op.cit.). In both the eastern tropical Atlantic and the EPO, yellowfin juveniles are distributed near to the shore. Adults make trophic migrations towards higher latitudes during the summer and genetic migrations across the ocean (Bard et al. 1999; Schaefer 1998).

All yellowfin stocks are considered to be fully exploited or overexploited. Increase in fishing effort would not be expected to result in sustained increases in catch. The recent world catches of this species have averaged about 1.3 million t, of which about 800000 t are from the Pacific, 400000 t from the Indian Ocean, and 125000 t from the Atlantic (Joseph et al. 2010).

Katsuwonus pelamis (Skipjack tuna)

Skipjack tuna is an epipelagic species generally inhabiting open waters. Aggregations of this species tend to be associated with convergences, boundaries between cold and warm water masses, outcrops and other hydrographic discontinuities (Collette and Nauen 1983). In the eastern Atlantic is found along the entire length of the West African coast (Diouf and Amon-Kothias 1993) while in the EPO is distributed in the Baja California coast and the central and South America coasts (Wild and Hampton 1994). The common sizes range between 30 and 80 cm fork length and the maximum is about 108 cm. Skipjack tuna can be found in waters with surface temperature from 18.8 °C to 26.2 °C (preferred temperature; Boyce et al. 2008). Depth distribution ranges from the surface to about 260 m during the day, remaining close to the surface during the night (Collette and Nauen 1983). Skipjack tuna breed opportunistically throughout the year over wide areas (Cayré and Farrugio 1986). This species occur within the 15 °C or warmer isotherm of the world oceans (Matsumoto et al. 1984). In the eastern Atlantic, migrations generally follow the coastline, both north-south and south-north, and westward in the equatorial zone (Bard et al. 1993). In the EPO a large fraction of the pre-recruit (35-45 cm) skipjack that disperse from the central Pacific migrate towards the coast of Central America (Wild and Hampton 1994). One portion, the northern group, enters the Baja California-Revillagigedo Islands area, while the southern group proceeds to the region off Central America to northern Chile (Williams 1972).

Skipjack is nowadays the most productive tropical commercial tuna. In recent years, the average catch has been about 2 million t per year. Of these 2 million t, about 1.5 million are from the Pacific, about 450000 from the Indian Ocean and about 140000 from the Atlantic (Joseph et al. op. cit.). In the eastern Atlantic Ocean is suggested that skipjack may be locally fully exploited, but the whole stock as well as in the Western Atlantic or other oceans are probably not yet fully exploited.

Thunnus obesus (Bigeye tuna)

Bigeye tuna is an epipelagic and mesopelagic species generally inhabiting open waters. The main environmental factors affecting the vertical distribution of this species are the depths of the deep scattering layer and temperature (Maury 2005). In the Atlantic Ocean bigeye tuna is found from 40 °N latitude to 35 °S longitude while in the EPO from about 40°N to 30°S (Miyabe 1994). Bigeye tuna sizes are frequently between 35 and 190 cm FL and the maximum size is over 200 cm. The water temperature preferences of this species range from 17° to 22.3 °C (Boyce et al. 2008). Notice that bigeye tuna is not found in waters where temperature exceeds 29 ºC (Collette and Nauen 1983). In addition, when the bigeye dives to great depths it is exposed to temperatures at about 5 ºC range (at 500 m; Brill et al. 2005). In the Atlantic Ocean juveniles are present throughout year in the equatorial zone and more seasonally in boreal and austral summer in the north and south tropical zones, respectively, forming mixed schools with skipjack and yellowfin juveniles, while pre-adults migrate northward (Senegal and Sherbro) and southward (Angola) from the Gulf of Guinea (Bard et al. 1993). In the EPO, since the thermocline rises toward the surface, bigeye tuna (especially larger ones) are found nearer to the surface (Bayliff 1980). Bigeye juveniles are found mainly in the equatorial region, also forming mixed schools, while adults are found along and off Central America coast (Bayliff 1980).

Prior to 1980, most bigeye was captured by longliners which take mostly large fish near the size that results in maximizing the yield per recruit. With the widespread use of FADs by purse seine vessels, large quantities of small bigeye have been caught, resulting in a decrease in the average weight. The world catches of bigeye have averaged about 450000 t in recent years: 230000 t from the Pacific, 80000 t from the Atlantic, and 140000 t from the Indian Ocean (Joseph et al. 2010).

1.4.2 Environmental conditions in the Atlantic and Pacific oceans: an overview

The eastern tropical Atlantic and the eastern tropical Pacific oceans, where the EU and Mexican tropical tuna purse seine fleets operate respectively share many common climatological features such as easterly trade winds, eastward shoaling thermocline, an eastern cold tongue and a northerly Inter-Tropical Convergence Zone (1TCZ). However, a comparison of climate variability between the two oceans reveals differences (Xie et al. 1999). The Pacific is dominated by the equatorially symmetric El Niño-Southern Oscillation (ENSO) while the Atlantic ITCZ is controlled by changes in inter-hemispheric sea surface temperature (SST) gradient (Xie et al. 1999). As a consequence, Pacific Ocean is characterized by a large yearly variability and a low seasonal variability while this is the opposite for the Atlantic. The environmental characteristics of each region are described below. A more detailed description of the environmental conditions in both oceans is provided in Annex T1.

1.4.2.1 The eastern Atlantic Ocean

The tropical Atlantic Ocean is controlled by changes in inter-hemispheric SST gradient (Xie et al. 1999), moving the ITCZ north-southward most pronounced in boreal spring when the seasonal warming occurs.

In the tropical Atlantic Ocean, the Canary current runs along the Moroccan and Mauritanian coasts, feeding the North Equatorial Current (NEC) around 20°N latitude (**Figure 1.7**) which flows westward and weakens during June-September. In this region, the Canary Current upwelling reaches its southernmost extent in winter. Between 10°N latitude and 20°N latitude upwelling becomes semi-continuous with a spring maximum (Chavez and Messié 2009) and a corresponding maximum of chlorophyll *a* (Chl *a*). Between 4° and 8°N latitude, the North Equatorial Countercurrent (NECC) flows eastward (**Figure 1.7**), presenting strong seasonal variations. The Guinea Dome is centered at 12°N latitude and 22°W longitude, which is associated with the NECC and the NEC flows and is characterized by a shallow thermocline. The NECC is extended into the Gulf of Guinea along African coast by the Guinea Current (**Figure 1.7**). In this region, the upwelling along the coasts of Côte d'Ivoire and Ghana occurs from July to September, driving the biology of the system in the Gulf of Guinea (Binet and Marchal 1993).

In the southern hemisphere the Benguela Current extends northward along the Namibia coast, and shifts to the west around 17°S. The westward flow of the Southern Equatorial Current (SEC) is divided into three branches and is more developed than the NEC. The Equatorial Countercurrent (EUC) flows eastward, rising in the eastern Atlantic. The SST in the Gulf of Guinea varies between 27°C and 29°C outside of the upwelling seasons (Allersma and Tilmans 1993), but can drop to below 22°C at the coast during the major upwelling (Binet and Marchal 1993). Stratification becomes enhanced during the warm seasons, especially the long warm season. The depth of the tropical thermocline can vary seasonally between 10 and 60 m in the Gulf of Guinea (Hardman-Mountford and McGlade 2003). The largest seasonal fluctuations of the SST in the tropical Atlantic Ocean occur in the Gulf of Guinea. From June to September the equatorial upwelling, injects nutrients into the upper mixed layer leading to surface Chl *a* and primary production maxima. Its onset and duration is subject to interannual variability (Signorini et al. 1999) associated with the ITCZ displacement.

In the eastern tropical Atlantic there are two core of oxygen minimum located in the Guinea dome and in the Angola dome, respectively. The poleward extent of the OMZ in the eastern South Atlantic is similar to the extent in the North Atlantic. The southern limit of the OMZ is the Benguela Current transporting oxygen rich water northwestward into the tropical South Atlantic. The oxygen supply to the OMZs is mainly from the west with near-equatorial currents (Karstensen et al. 2008). The surface concentration increases progressively toward the south as a result of the cooling of waters which increases the solubility of oxygen. This cooling permits the oxygenated homogeneous layer to thicken. At the equator the oxycline approaches the surface and the oxygen content shows a minimum. The equatorial divergence, less rich in oxygen, depletes the surface layer (Gouriou 1993).

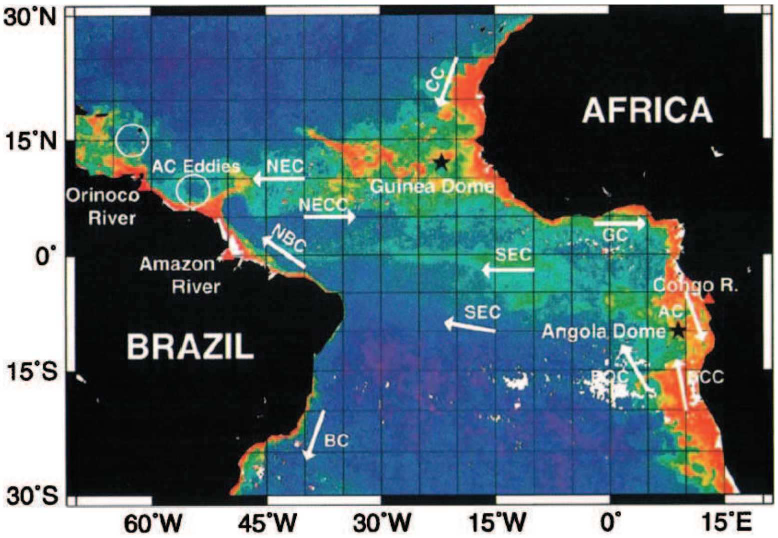

Figure 1.7 Schematic representation of tropical and subtropical Atlantic currents. A SeaWiFS Chl a image for the month of November 1997. Source: Signorini et al. 1999

The Atlantic equatorial mode (or Atlantic Niño) is an interannual phenomenon similar to but weaker than the Pacific El Niño (Wang 2005). The warm events reach their maximum strength in the second half of the year, with manifestations focused primarily near the equator. During this phase, ascending motion associated with the Intra-Americas Sea-Amazon heat source extends eastward (Wang 2002). This eastward extension weakens the Atlantic Walker circulation and thus decreases surface equatorial easterly wind in the western Atlantic. This process increases SST in the equatorial eastern Atlantic (Wang 2005) deepening the thermocline in this region. The Atlantic equatorial mode is mostly independent of the ENSO variability. It has a shorter characteristic time scale and is not to be confused with the tropical Atlantic response to the ENSO (Wang 2005).

1.4.2.2 The eastern Pacific Ocean

The environmental conditions in the EPO throughout year depend on the space-time variability patterns of Intertropical Convergence Zone (ITCZ) (Amador et al. 2006). The direct effects are most evident in the distributions of SST, sea surface salinity (SSS), the depth and strength of the thermocline, and the depth of the surface mixed layer (Fiedler and Talley 2006). Ekman pumping generates coastal and open-sea upwelling, as well as fronts, eddies and meanders (Willett et al. 2006). More indirect effects operate through dynamical processes like geostrophic balance and Rossby and Kelvin waves, all of which involve the topography of the thermocline (Kessler 2006). Instability of the currents can also generate eddies and meanders.

The fact that the ITCZ is always in the northern hemisphere and that it oscillates seasonally between ~5°N (in winter) and ~10°N (in summer) have profound consequences for the oceanography of the EPO. West of Mexico and Central America the wind is weak, consequently the thermocline is shallow and strong in this area (the eastern Pacific warm pool; **Figure 1.8**), and SST is higher than elsewhere in the region (Fiedler and Talley 2006). A distinct and prevalent association between specific seabirds, yellowfin tuna, and certain dolphin species is characteristic of the warm pool region (Ballance et al. 2006). The EUC is driven by an eastward-directed pressure gradient. The EUC flows within the equatorial thermocline until it approaches the Galapagos Islands, being a source of nutrients upwelled along the equator (Pennington et al. 2006). The equatorial upwelling has a moderate seasonal variability, phytoplankton and zooplankton biomasses are largest in summer and autumn (Fernández-Alamo and Färber-Lorda 2006; Pennington et al. 2006).

Below the ITCZ at ~10°N, where the NECC eastward flow (**Figure 1.8**) transports high nitrate concentration and increased production, during spring the NECC flow is weak or absent (Kessler 2006; Pennington et al. 2006). The NECC splits to turn into the SEC and into the NEC (**Figure 1.8**), and is an important physical feature for many top predators (e.g. tuna, dolphin, seabird; Ballance et al. 2006). The NEC and the SEC are the major westward components of the equatorial current system in the EPO, reaching their greatest strength during the winter of their respective hemispheres. The Costa Rica Dome is an upwelling region, with seasonal variation in size, being smaller in February-March and bigger in summer-fall (Fiedler and Talley 2006). Primary and secondary productions are relatively high at the Dome, supporting tuna and other fisheries (Ichii et al. 2002). The Peruvian coastal upwelling is the most important in the EPO (Kessler 2006; Pennington et al. 2006), caused by equatorward trade winds, but is susceptible to interannual variability caused by the ENSO. The equivalent eastern boundary in the northern hemisphere is the California upwelling, and it is an important input and boundary condition for the region (Pennington et al. 2006). During winter, wind jets occur (the Tehuantepec Jet, the Papagayo Jet and the Panama Jet) in the warm pool, inducing thermocline lifting (Willett et al. 2006; Pennington et al. 2006). However, the SST and chlorophyll anomalies in this region are due to intense vertical mixing below the axis of the wind jet (Willett et al. 2006). The shallow and strong thermocline is characteristic in the entire EPO, indicating that the exchange of properties (e.g. dissolved oxygen) between the surface waters and the subsurface layers is very weak. The OMZ is very pronounced, with lower oxygen concentration than other OMZ areas in other oceans and it can be present a few tens of meters from the surface (Fiedler and Talley 2006).

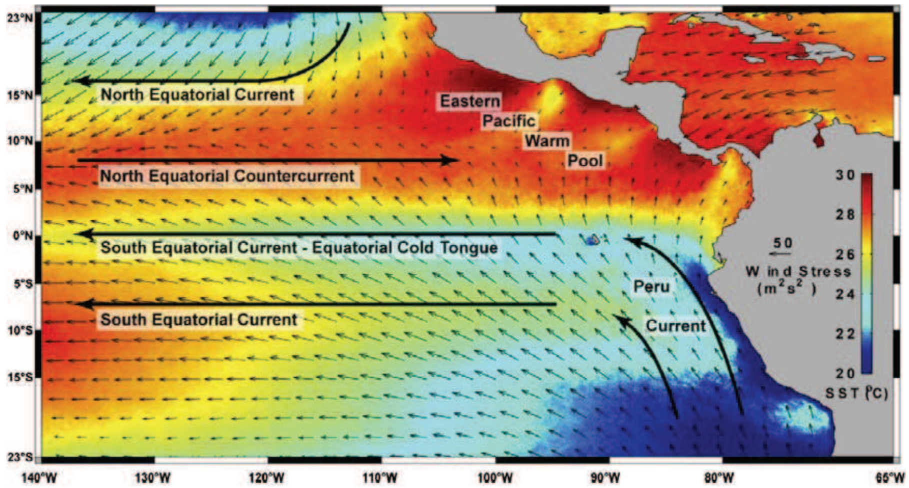

Figure 1.8 Average sea surface temperature (color scale), wind stress (thin arrows) and overview of major surface currents (thick arrows) in the eastern tropical Pacific. Source: Pennington et al. 2006.

El Niño-Southern Oscillation, ENSO

In the Pacific Ocean, the ENSO is characterized by unusually warm temperatures and encompasses variability in both the eastern and western tropical Pacific. This variability is most pronounced along the equator and the coast of Ecuador and Peru but is closely related to variability of the tropical warm pool (Wang and Fiedler 2006). ENSO-related changes in winds, insolation, hydrography and circulation in the EPO are of sufficient magnitude and duration to affect organisms, populations and ecosystems.

Among the physical effects of El Niño are a deepening of the thermocline and nutricline, and it has a negative effect on primary productivity (Pennington et al. 2006). This affects the survival, reproduction and distribution of higher trophic level organisms (Ballance et al. 2006). During the El Niño threshold, the equatorial thermocline flattens, the EUC weakens, and the NECC strengthens (Kessler 2006). The productivity in the Costa Rica Dome diminishes considerably (Pennington et al. 2006).

1.5 Tuna purse seine fishery management

World's tuna fisheries are at a critical juncture, with most tuna stocks fully exploited and some overexploited. All of them facing growing fishing pressures from overcapacity and the ongoing development of technology. The conservation and management of these highly migratory species are complicated by the transnational nature of tuna stocks. It should be kept in mind that stocks are shared among EEZs, but also extend to the high seas beyond the EEZs (about 40% of the world's tunas are captured on the high seas). Such a situation creates conservation and management issues of jurisdiction, property rights, international law, and multilateral cooperation. Limited entry into tuna fisheries, and in general, an even greater strengthening of property rights coupled with multilateral cooperation, are required to prevent overexploitation of the world's tuna stocks, further overcapacity, and declining profitability and socioeconomic benefits (Allen et al. 2010).

1.5.1 Regional fisheries management organizations (RFMOs) and management objectives

As stated earlier, the tuna fisheries are more challenging than many other fisheries, because these highly migratory fish do not respect any EEZs. Membership of the RFMOs are composed of both coastal countries and distant-water fishing countries. Each RFMO has an independent scientific committee (e.g., the Standing Committee for the Research and Statistics in ICCAT) or a scientific staff (e.g., IATTC) that is responsible for assessing the condition of the tuna stocks and developing management and conservation recommendations.

The report of October 2003 IATTC Workshop on Reference Points for Tunas and Billfishes (http://www.iattc.org/Meetings2003/Meetings2003ENG.htm; IATTC 2003) summarizes the management objectives of the tuna-RFMOs and the US National Marine Fisheries Service. Much of that report is summarized in Annex A2, especially the objectives and organization of the RFMOs responsible of Atlantic Ocean (ICCAT) and the eastern Pacific Ocean (IATTC).

While the objectives are clear (e.g., reference points as MSY), the tuna RFMO process is not conducive to the acceptance of science-based recommendations. The decision making process is generally based on a consensus of the members, and, given the many differing national interests, agreement is extremely difficult. Even when agreements are reached, they tend to be reduced versions of the recommendations made by the scientists. The subsequent interpretation of the regulations and enforcement by the tuna RFMOs members varies considerably (Joseph et al. 2010).

1.5.2 Management measures

In established/mature fisheries, such as tuna fisheries, RFMOs tend to concentrate on how to assess the status of the stocks and how to control fishing effort. Stock assessments provide recommendations on what level of removal is appropriate for fish stocks, but fisheries managers must choose how to control catches (Branch et al. 2006). Management often starts with input controls, including restrictions on season-length, engine horsepower, tonnage, hull construction, gear types, the number of crew members on board, and vessel entry. However, input controls almost always result in a less efficient fishery (both technically and economically) because they restrict methods of capturing instead of restricting catch directly (Salas and Gaertner 2004). These options generally cause or exacerbate a “race for fish” and excessive investment (Branch et al. op.cit.). Given tuna management objectives, the RFMOs are empowered to coordinate and/or conduct research on the fish and the fisheries covered by them. The degree to which the RFMOs have been successful in achieving their objectives has varied. The two oldest RFMOs, the IATTC and ICCAT, were created before there was enough fishing capacity to cause overfishing problems (Joseph et al. 2010). However, as the fishing capacity increased, controls to prevent overfishing were needed.

ICCAT’s first management measures were in the form of output controls. It was established a minimum-size limit of 3.2 kg for yellowfin tuna in 1973, and a similar minimum-size limit for bigeye in 1978 (Fonteneau et al. 1993). The rationale for establishing the minimum size limit on yellowfin was to increase the yield per recruit, while for bigeye was primarily the fact that bigeye and yellowfin of less 3.2 kg are difficult to distinguish from one another (Fonteneau 1976).

In the mid-1990s, the ICCAT was aware of the large increase in the catches of bigeye tuna and juveniles observed since the early 1990s in the Atlantic Ocean. Hence, within the framework of the Bigeye Tuna Year Program (BETYP), ICCAT requested that further analysis be carried out on these issues to determine protected fishing areas and seasons through observer programs for all type of fleets. From the European Reseach program conducted jointly by IRD and IEO on EU purse seiner fleets , different assumptions were raised to explain the increase in juvenile catches. Among others, a change in catchability due to the extension of the use of FADs, in eastern Atlantic areas fished historically on unassociated schools or in new areas towards 35°W longitude (Ariz and Gaertner 1999). In such a context, the French and Spanish tuna boat owner companies implemented a voluntary protection plan for juvenile tunas in 1997, consisting of a ban on FAD-fishing operations during a three-month period over a large portion of the Gulf of Guinea (ICCAT [96-01]; **Figure 1.9**). This moratorium was adopted and extended to all surface fleets by ICCAT in 1999. As there were no change in terms of time and area closure since the voluntary moratorium, the entire period of 1997-2005 will be termed hereafter as moratorium on FADs. In 2004, ICCAT adopted recommendation [04-01] "Multi-year conservation and management program for bigeye tuna", with the goal of conserving and managing bigeye tuna stocks and because of the concern about the increase in illegal, unreported and unregulated (IUU) fishing activities. This recommendation entered into force in June 2005, and consisted in resizing the area limits of the former recommendations and reducing the months' period (**Figure 1.9**). Unlike recommendations [98-01] and [99-01], which banned the use of FADs, recommendation [04-01] prohibited tuna catches in the restricted stratum for all surface fishing gears, which will be termed hereafter as closure or no-take area. These spatial regulations will be addressed in Chapter 3.

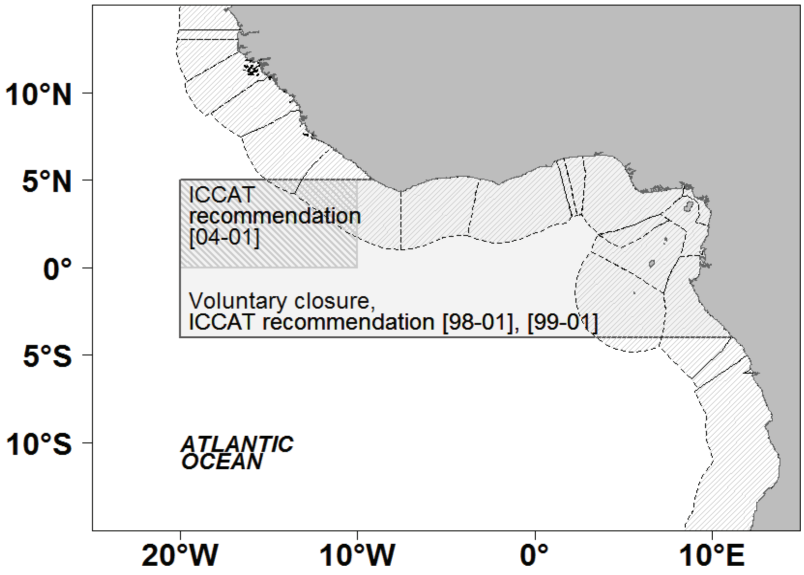

Figure 1.9 Zones of the different spatial regulations: (1) the voluntary moratorium and ICCAT recommendations [98-01] and [99-01] on FADs were instituted during the period 1997-2005 from November to January (gray rectangle), (2) the no-take regulation in November that replaced the moratorium on FADs was in the Piccolo zone from 2005 up to the present (small shaded rectangle). The shaded contour represents the economic zones (200 nautical miles).

The first international conservation measures for tuna were introduced by the IATTC in the mid-1960s in the EPO in the form of a yellowfin catch limit with free competition, i.e. the quota was not partioned by flag state or vessel (Joseph et al. 2007). Under this measure, when the catch approached the limit, the Director of Investigations of IATTC decided the date of closure. However, each vessel that left port before the closure date was allowed to complete its trip. This measure had the unintended consequence of encouraging the construction of purse seiners with greater holding capacity. For many years following 1979 no regulations were implemented because biomass was greater than B_{MSY}.

The use of catch limits has been established to yellowfin and bigeye tunas mainly because of the increase in fleet size. Since 1990 when the yellowfin catches were close to the limit, the Director was authorized to increase this limit by up to three successive increments (in average 20000 t) if he concluded from examination of available data that such increases would pose no substantial danger to the stocks. Regarding bigeye tuna, the concern about the increase in the catches of small bigeye by the purse seine fishery led the IATTC in 1999 to adopt conservation measures to restrict fishing on floating objects of all types. Once the catch limit (45000 t) was reached it was banned the FAD-fishing. However, the fishing effort increased continuously, reaching levels above the average MSY levels for both species in the period 2000-2001. IATTC recognized in 2002 that the potential production and specifically recruitment may be affected by this excessive fishing effort and, as a consequence, implemented a limitation on the catches of the purse seine fishing and a closed season from December 1 to December 31 [resolution: C-02-04].

In 2004 IATTC adopted a new resolution [C-04-09] "Multi-annual program on the conservation of tuna in the eastern Pacific Ocean for 2004, 2005 and 2006" because the concerning of the increasing catches of bigeye tuna by longliners and the continuous increase in fishing capacity. This resolution resolved two closed seasons for purse seine fishing, one from August 1 to September 11 and the other from November 20 to December 31, this resolution was lengthened until 2007. Each IATTC contracting country had the possibility to choose which of the two periods would be closed to its own purse seiners, the Mexican tuna purse seine fleet chose the second closed season. Then in 2009 and in 2010-2011 a closure of 59 days and 62 days, respectively, divided in two periods during each year. During these years the purse seine fishery was closed in the area of 96° and 110°W longitude and between 4°N latitude and 3°S latitude from September 29 to October 29. The season-length restrictions will be addressed in Chapter 3.

1.5.3 Fisheries agreements

In the beginning of the tuna purse seine fishery in the Atlantic Ocean, the displacement of the vessels in inshore of the coastal countries of the African West Coast was carried out without problems before the independence of these countries. The recognition of the EEZs during the 1970s led the fishing industry owners and the governments (Europeans and Africans) to establish fishing agreements (Couliou 2001). These agreements introduced finanacial terms, clauses on the use of national fishermen on board the French purse seiners, and catch volumes were fixed. These agreements have been established with Cape Verde, Sierra Leone, Liberia, Guinea Bissau, Guinea Conakry, Ghana (in 2010 and 2011), Côte d'Ivoire, Sao Tomé and Principe, Gabon and Angola. In the case of Mauritania and Senegal, fishing agreements were not renewed from 2005 and 2006 respectively (M. Goujon, pers. comm.).

In the EPO, the prevailing policy around the mid-1960s regarding fisheries for tunas was that access beyond 3 nautical miles of the coastline was open to the citizens of any nation who wished to fish. The resource was considered to be a common property of, and to belong to whoever could first render it to his use. Due to the TAC implemented, once it was filled all would have to halt fishing for that species. This resulted in a race for the fish, and progressively shorter seasons as the fleet capacity grew. These facts caused increasingly greater confrontation among nations with large fleets capable of taking a large share of the catch before closure. Most of these fleets were distant-water fishing nations, while nations with small fleets were developing coastal countries. The coastal countries maintained that a share of the resource should be allocated to them by virtue of the fact that the tunas spent time in waters under their jurisdictions, and the recognition on the EEZs. The large fleets maintained that the tunas were a common resource and belonged to whoever could catch them (Joseph et al. 2010). This issue derived in a problem between Mexico and US, the latter in 1980 imposed an embargo to Mexico by the seizure of US vessels which had been fishing within Mexico’s EEZ. In 1986 the embargo was lifted because Mexico agreed to discuss regional, rather than national, regulation of tuna, which would allow access by US vessels to tuna in Mexican waters. It supposed that Mexico was agreed to limit tuna exports to the US voluntarily to avoid harming the US tuna industry domestically (DeSombre 2000).

ANNEX A1

Purse seine fishing operation (Figure A1)

1. When a school is detected, the vessel places itself aside the school. The skiff, attached to one extremity of the purse seine and having one extremity of the purse line cable (whereas the other extremity of this cable is attached to the winch on the purse seiner) is released.

2. The vessel then encircles the school at maximum speed. Usually, all the purse seine is set and the circle is closed within 4 to 8 minutes. Tunas can change their direction and escape before the circle is closed.

3. Once the encirclement is finished, the extremity of the net that stayed attached to the skiff is transferred aboard the purse seiner and the two extremities of the purse line cable are hauled with the winch as quickly as possible in order to close the net at its bottom. Until the purse seine is not closed, the tunas can still dive below the net or the purse seine vessel and escape. In the eastern Pacific, when the set is made on dolphin-associated school, a special operation, known as the "backdown operation" is realized at this time in order to let a par of the float line submerge in the water so that dolphins having been trapped in the purse seine can be released through that section. Speed boats are used to hep release operation. The pursing may take for large purse seines around 15 to 20 minutes.

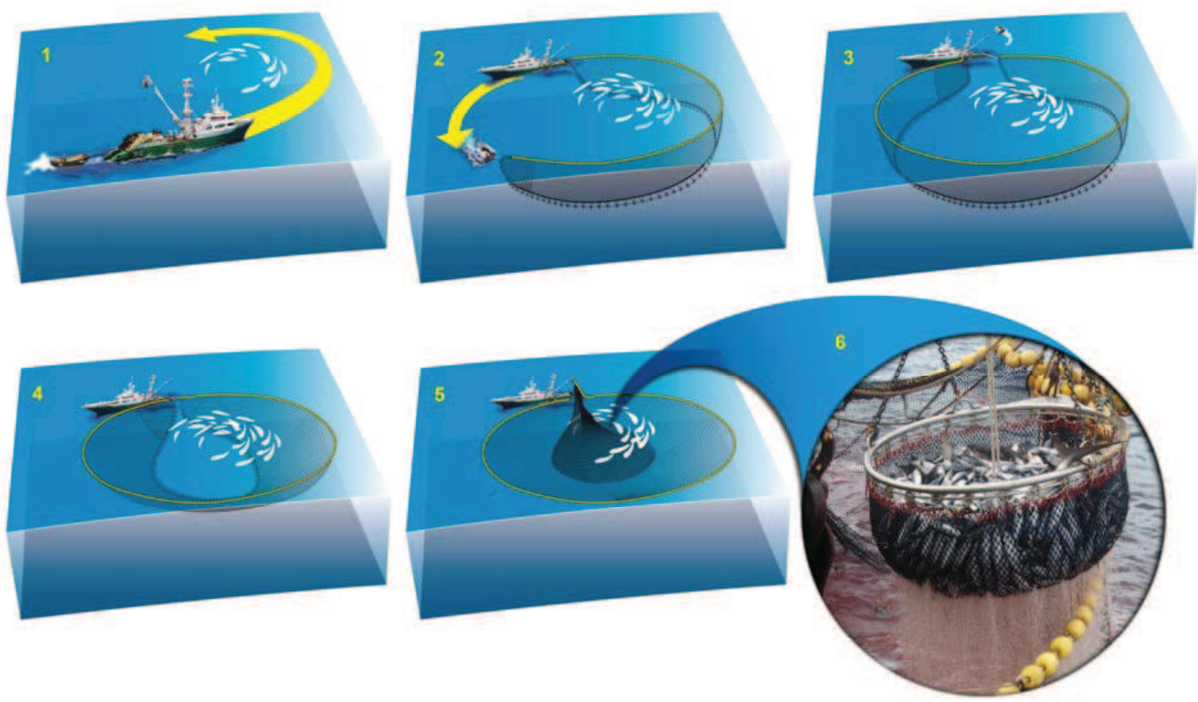

Figure A1 Different phases in the deployment of a purse seine. Numbers correspond to the respective number of paragraph. © IRD, EME.

4. The net is pulled aboard the purse seiner with a hydraulic power block. Under the power block, the net is stacked on the stern of the boat by fishermen in such a way that it will come smoothly off the stern at the beginning of the next set. As a whole, this operation will, if there is no incident, take around one hour or even longer, depending on the size of the net and catch.

5. When most of the purse seine has been retrieved, the tunas have been grouped within a restricted area along the portside of the vessel. Then the fish are harvested from the purse seine using a large scoopnet called the "brailer" (brailing operation); several tonnes of fish are taken on board each time. The duration of this operation will obviously depend upon the quantity of fish in the net.

6. The tunas go towards fish-wells through trays and tubes arranged in the deck. In the fish-well fish are in brine which cools the fish without delay and freeze it for long conservation at -20 °C or even lower.

ANNEX A2

Objectives and organization of the ICCAT and IATTC

The ICCAT Convention specifies as one of its objectives the "maintenance of the populations... at levels which will permit the maximum sustainable catch and which will ensure the effective exploitation of these fishes in a manner consistent with this catch." Thus, the implicit target is the biomass corresponding to the maximum sustainable yield (B_{MSY}) and/or the fishing mortality corresponding to MSY (F_{MSY}). In practice, ICCAT has mandated rebuilding plans for several overfished stocks. In these cases, the target has been to reach B_{MSY} by a given year with a probability of 50% or greater.

SCRS-ICCAT assessment working groups thus attempt to estimate B_{MSY}- and F_{MSY}-related benchmarks with a variety of methods. More attention is paid to ratio statistics (e.g. B_t/B_{MSY}, where B_t is the biomass at time t), than to absolute quantities. However, a variety of results may be taken into consideration together when communicating uncertainty to the Commission.

The guidelines for limits and targets in the 1995 United Nations Fish Stocks Agreement are potentially in conflict with ICCAT's implicit F_{MSY} target. ICCAT scientists have recommended that management control rules, that define both limits and targets, be identified and evaluated for various stocks. In the 1949 Convention of the IATTC the formal management objective is to keep the populations of fish at levels that will provide the MSY. The species specifically mentioned in the Convention are yellowfin, skipjack, baitfishes, "and other kinds of fish taken by tuna fishing vessels". The management objective can be used to define a reference point, which could be seen as either a limit or a target reference point.

While in the 1949 Convention is provided the formal objectives, in the new "Antigua Convention" (2003; and entered into force in 2010) gives a current perspective on the thinking of the member countries. The management objectives of the Antigua Convention do not contradict the earlier ones. The Antigua Convention preserves the general objective of maintaining populations of harvested species at levels that can produce the MSY. Some of the key new points are (1) Application of the precautionary approach; (2) a different objective for species belonging to the same ecosystem, and (3) a specific reference to measures to prevent excess fishing capacity.

The IATTC considers several reference points and related quantities in its annual Stock Assessment Reports. Reference points are generally more developed for the main tuna species (yellowfin and bigeye), but are also presented for several species of billfish. Spawning biomass ratio (SBR) is the ratio of the spawning biomass to the average spawning biomass in the absence of fishing. This quantity is compared to the SBR required to produce the MSY (SBR_{MSY}).

MSY is calculated based on the current age-specific fishing mortality. It is also calculated using the age specific fishing mortality based on a single fishery, allowing the comparison of the efficiency of each fishing method in respect to maximum yields. The associated SBR is also presented. MSY and SBR are also calculated for two different productivity regimes for yellowfin. Sensitivity analyses, particularly to the steepness of the stock-recruitment relationship, are used to show the sensitivity of the reference points and indicators.

Chapter 2

Effects of new fishing technology on the fishing strategies and tactics of the tropical tuna purse seiners operating in the eastern Atlantic Ocean

2.1 Introduction

Whatever the domain of activity considered, new technologies have been implemented over time with the aim to make human activities easier. Regarding fishing activities, the use of new technology has for objective to catch more fish and/or to improve the quality of landings (Kennelly and Broadhurst 2002). The main purposes of investment by the fishing industry are twofold: (1) increasing benefits or saving on other areas of their operations (e.g., operating costs, reduced labor, improved crew safety), and (2) facing regulations about fishing effort (Ward and Hindmarsh 2007). Fishery investment is part of fishing fleet behavior and may consist in acquiring new vessels and investing into new technology that will result in changes in fishing efficiency (e.g. gain on catchability in previously known fishing grounds) and tactics (e.g. access to new fishing grounds) of the fleet. By increasing fishing efficiency and, developments in fishing gear and practices generally modify the relationship between catch rates and abundance (i.e., catchability), which forms the core basis of input data for stock assessment models and resulting management advices (Hilborn and Walters 1992; Bishop 2006). Monitoring and evaluating investment in fishery technology is therefore crucial to improve (1) the assessment of stock status of fisheries resources (Marchal et al. 2001; Ward 2008), (2) the management of fisheries based on direct control of nominal fishing effort that should be explicitly linked to effective fishing mortality (Marchal et al. op. cit.), (3) the evaluation of economic performance of fisheries (Pascoe and Robinson 1996; Ulrich et al. 2002), and (4) our understanding of fleet dynamics so as to better anticipate fishermen behavior in the face of changes such as increased oil price or implementation of regulatory management measures.

In the case of tuna purse seine fisheries, tropical tunas are highly mobile species, which results in large variations in fish availability in space and time (Cayré et al. 1993; Lehodey et al. 1997). When environment conditions are suitable, adult tuna aggregate into unassociated schools that gather into large concentrations (Stretta 1993; Ravier et al. 2000; Fonteneau et al. 2008). The association of skipjack and juveniles of yellowfin and bigeye with floating objects constitutes large schools, although the reasons of such behavior have not been fully resolved (Hall 1992; Fréon and Dagorn 2000; Castro et al. 2002). Skipper’s decisions regarding when and how to exploit tuna concentrations and how to use devices to detect the presence of tuna schools at the sea surface lead to concepts such as fishing strategies and tactics (Laloë and Samba 1991; Ferraris 1995; Gaertner et al. 1998). Here, strategy is defined as the combination of fishing tactics (i.e. a short-term decision using a specific fishing mode such as free-swimming schools vs. FAD-fishing) and fishing grounds (in a large spatial and temporal decision or resulting from the succession of fishing tactics) at a given time of the year. For the sake of simplicity we define a strategy as the action which consists to decide to fish on free-swimming schools or on FADs on the long-term, and a tactic as the spatio-temporal strata where each strategy is deployed over the year. Although purse seiner strategies ultimately depend on the skipper decision, they are influenced by the economic investment made by tuna ship owners, i.e. high capital investment in FAD-fishing for construction, maintenance, deployment, and geolocation of FADs, by the probability of set success which is higher on FAD-associated than on free-swimming schools, and by the size range of the target species and associated expected value, i.e. high-priced large yellowfin tunas vs. low-priced skipjack and small yellowfin and bigeye tunas (Guillotreau et al. 2011).

The relationship between catch per unit effort (CPUE) and abundance may be biased over time due to changes in fishing power (e.g. introduction of new electronic devices, artificial logs, satellite imagery) which are difficult to evaluate (Arreguín-Sánchez 1996; Fonteneau et al. 1999). This increase in fishing efficiency and catchability over time has tentatively been analyzed in some tuna fisheries through the improvement of vessel and gear attributes, and introduction of technology (Hervé et al. 1991; Gascuel et al. 1993; Le Gall 2000; Morón et al. 2001; Gaertner and Pallarés 2002; Itano 2003; Miyake 2005). However, none of these studies assessed the consequences of fishing mode-specific technological changes on fleet strategies.

The aim of this chapter is to investigate to which degree the introduction of new technology on board affected the fishing efficiency related to each strategy and the tactics in space and time of the French purse seine fleet in the eastern tropical Atlantic Ocean from 1981 to 2008. Based on two indicators describing the two major fishing modes of the fishery, i.e. free-swimming schools sets and FADs sets, (1) we describe the yearly changes in the fishery based on a group of representative vessels, (2) we look for sudden changes in the indicator time series to define homogeneous time periods corresponding to characteristic regimes in the purse seine fleet strategy, (3) we define time-space strata within each time period through clustering approaches to analyze the spatio-temporal patterns of the fishery, and (4) finally we use a point pattern approach to describe the changes in spatial distribution of the fleet according to time-space strata.

2.2 Materials and Methods

2.2.1 Fine-scale operational data

Logbook data and trip unloading and transshipment records from the French and associated tropical tuna purse seiners operating in the tropical eastern Atlantic Ocean have been collected by the Research Institute for Development (IRD) since the early 1970s. Species composition declared in purse seine logbooks has been known for some time to be biased due to species misidentification (Fonteneau 1976). Based on multispecies size-frequency samples collected at landing sites and a specific sampling design, a data processing has therefore been performed routinely since 1980 to correct for logbook species composition (Cayré 1984; Pallarés and Hallier 1997; ICCAT 2010). Therefore, logbook declarative data for the period 1981-2008 are used in preference to corrected data because they better represent tuna size categories for a specific set while corrected data reflect the species composition sampled over large time-area strata (**Figure 2.1**).

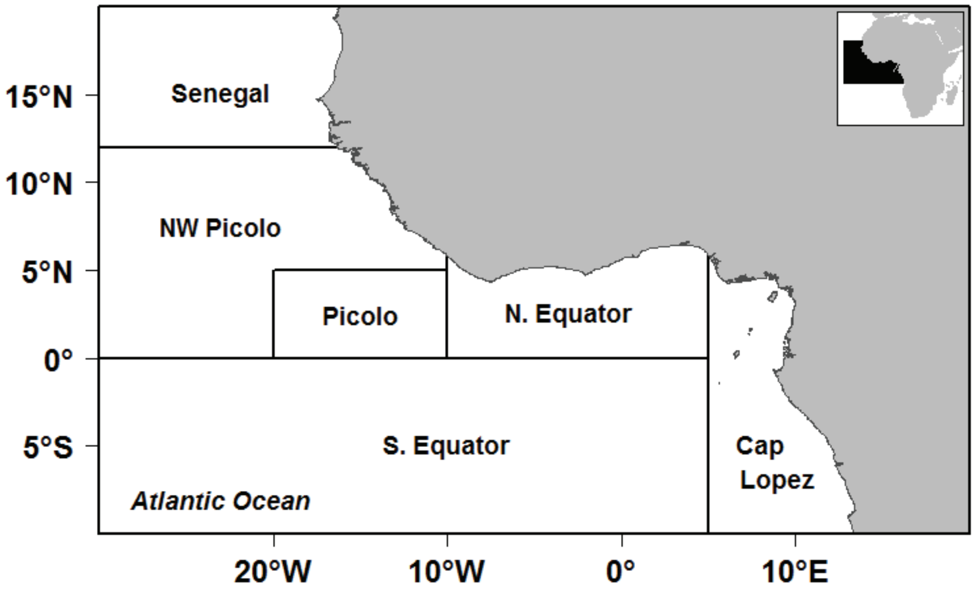

Figure 2.1 Location of the study area. Draw regions correspond to the spatial sampling strata used for the tuna species composition by the International Commission for the Conservation of Atlantic Tunas (ICCAT) for the purse seine fishery. They are given as a reference for interpretation in Results section.

2.2.2 Introduction of on-board new technology

French purse seiners have continuously been modernized over the last 30 years. Technological progress also originated from (1) the construction of new, better-equipped purse seiners and (2) the constant introduction and updating of technology on board of older purse seiners so as to maintain the fleet with an overall similar level of fishing power. A census of historical changes in the main technological innovations on board of the French purse seine fleet (bird radars, drifting FADs, supply vessels, GPS positioning buoys, tracking buoys, satellite information on environmental factors, sonars, echo sounders, purse winches, power blocks, purse seine size modifications, material used for the net, rail rollers, etc., Hervé et al. 1991; Fonteneau et al. 1999), was conducted through the EU Research project “Efficiency of Tuna Purse seiners and Effective Effort (ESTHER; see Gaertner and Pallarés 2002) (**Figure 2.2**). The dates of introduction compiled in ESTHER were provided by tuna fishing companies (SAUPIQUET and COBRECAF belonging to ORTHONGEL -French tuna boat owners association-) and updated for this analysis. Because French purse seiners preferentially target large yellowfin tuna compared to Spanish vessels, technology may differ between fleets and technological changes may have not occurred at the same time. For this reason, in this chapter we analyzed the consequences of the introduction of new technology on board the French purse seine fleet only.

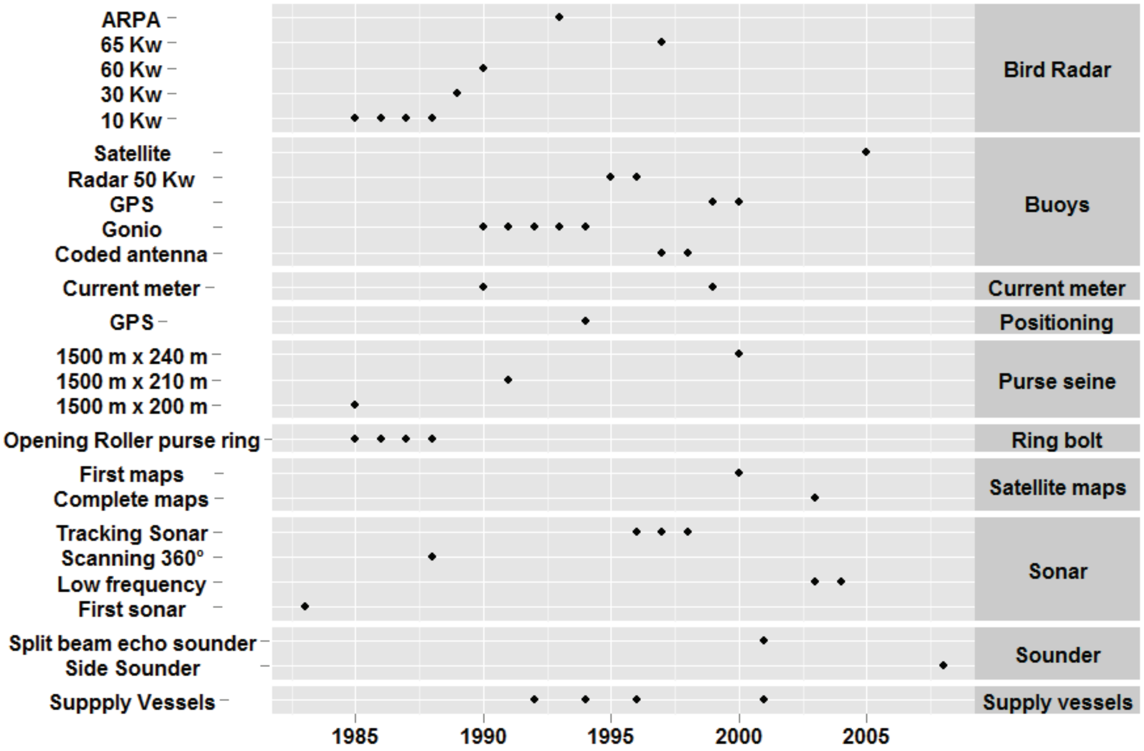

Figure 2.2 Dates of introduction of new technology on board of the French purse seine fleet operating in the eastern Atlantic Ocean. Source: ESTHER and updated with the cooperation of ORTHONGEL: M. Goujon, and SAUPIQUET: A. Claude.

2.2.3 Fishery indicators

Two indicators were used to describe the major output characteristics of the tropical tuna purse seine fishery: (1) the catches of juveniles of tropical tunas (< 1.8 kg) on FAD sets ($JuvC^+$) and (2) the number of sets made on free-swimming schools (*FrSc*). The use of the indicator $JuvC^+$ is justified because due to the introduction of FAD-fishing, the catches of juveniles of tunas have increased during the last 20 years with this fishing mode to a level that led the ICCAT to establish the time-space regulatory measures (described in Chapter 1). Moreover, the development of FAD-fishing extended the purse seine fishery to new fishing grounds. The second indicator (*FrSc*) is characteristic of the main fishing method that started with the beginning of the purse seine fishery in the early 1960s, concerning mainly large yellowfin tuna (> 110 cm). We consider that these indicators will better reflect changes in the fishing strategies, because they are directly involved in the searching and setting processes. Both indicators were estimated on a monthly basis for each vessel and normalized by the numbers of days-at-sea to avoid bias ($FrSc = \text{sets.d}^{-1}$, $JuvC^+ = \text{t.d}^{-1}$). These measures are sensitive to respond to slight changes due to an increase in fishing power because in general a vessel spends the same time at sea each month. We argue that due to the fact that several devices are involved in the purse seine fishing the indicators will include the concomitant and combined effects of such devices. For instance, if there is a reduction in searching time because of the introduction of efficient bird radars and a reduction in setting time with purse seine better designed then it would allow doing more operations than before the use of these devices, reflecting a global improvement in fishing efficiency. This increase in efficiency may be masked using fishing effort at a fishing activity level instead of fishing activities in a day. Fishing activity level may better reflect the effect of only one device. For all these reasons, we consider that our indicators are consistent with the aim of this study. It should be stressed that $JuvC^{+}$ is not used as a representative measure of abundance, but as an evidence of fishing efficiency. Although the time and duration of introduction of new technology varied among devices and might result in some delay through learning time, for instance, the effects of new devices on the indicators were expected to occur on the short term, i.e. within 1 or 2 years after introduction.

As the vessels did not all operate during the whole period, and to ensure that the results represent the effects of the introduction of new technology on board, only the 23 vessels presenting at least half the entire time period were taken into account. This assumes that the selected vessels gained more experience about spatial and temporal distribution of tuna, and in using new technology. The year 1999 was not included in the analyses dealing with free-swimming schools since the information on this fishing mode was not available at the time of this study.

2.2.4 Statistical analyses

For each fishery indicator (1) annual values were calculated from a linear mixed model (LMM), (2) sudden changes in each annual time series were investigated through a Bayesian analysis for change-point (BCP) to obtain homogeneous periods of time, i.e. blocks of years (Barry and Hartigan 1993), (3) monthly (seasonal) clustering was performed within each homogeneous block of years by using “Multi-regression tree (MRT) as a chronological clustering method” (Borcard et al. 2011), and (4) a point pattern analysis was used to highlight the intensity of the point patterns (i.e. the expected number of points per unit area) per season within the homogeneous blocks of years of each indicator. The complete procedure is summarized in **Figure 2.3** and described below.

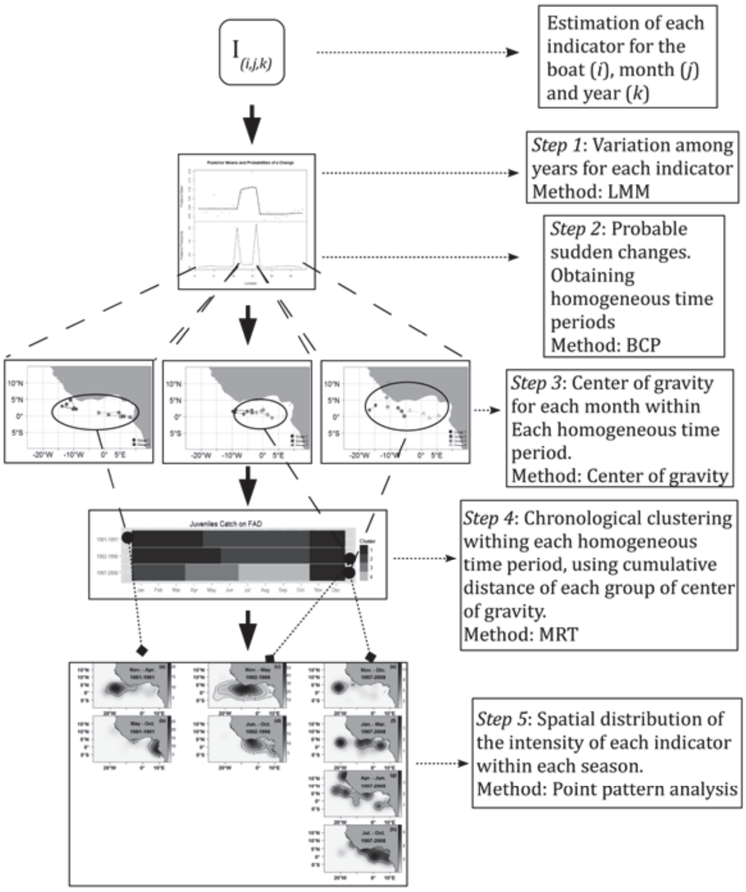

Figure 2.3 Schematic representation of the different analyses carried out in the present study (see Material and Methods for details).

Step 1: Calculation of the yearly index for each indicator

To study the yearly time series of each indicator, a linear mixed model (LMM) was used to remove both seasonality and vessel random effects. The use of random effects quantifies the variation among units, where the most common type of random effects are the blocks in experiments or observational studies that are replicated across sites or times, and these random effects account for two sources of variation: (1) within-groups and (2) among population effects (Laird and Ware 1982; Pinheiro 2006; Bolker et al. 2009). The LMM are often appropriate for representing clustered, and therefore dependent, data derived, for instance when observations are taken on related individuals or the data are gathered over time on the same individuals. LMM are very effective in situations where the data are very unbalanced or fragmentary (Venables and Dichmont 2004). For these reasons, we consider the use of LMM is appropriate to obtain the year to year variation of each indicator.

In this study the LMM used specifies that the values of each indicator and its responses vary randomly across the interannual and seasonal scales, and across vessels. The model design is expressed as follows:

$$Y_{ijk} = \gamma_0 + (u_{0i} + v_{0j} + w_{0k} + e_{ijk})$$

where Y_{ijk} is the fishery indicator, for i vessel, j month and k year. The γ_0 is the overall intercept. The four terms in the random part are the random effect of the unique component of each vessel u_{0j}, of each month v_{0k}, of each year w_{0l}, and the residual component e_{ijk}. From this model, each factor has a random-effect vector which is the standard deviations of variation at a particular level (i.e. from year to year, from month to month and from vessel to vessel), thus the interannual random-effect vector was used as the standardized annual fishery indicator.

Step 2: Analysis of regime shifts of each indicator over time

To assess regime shifts at unknown dates, a Bayesian analysis for change-point problems was used. In contrast with frequentist procedures which provide specific locations of change points, Bayesian analysis provides a probability of change at each position in a sequence of a series of independent observations collected over time. Let X_1, X_2, ..., X_n represent each indicator in time order. A simple change-point model can be written as follows:

$$X_i \sim p(x_i|\theta_1), \quad i = 1, \ldots, t$$

$$X_i \sim p(x_i|\theta_2), \quad i = t+1, \ldots, n$$

Where the density $p(x|\theta)$ belongs to a known class of probability densities, e.g. $N(\mu_1|\sigma_1^2), N(\mu_2|\sigma_2^2)$; t is called the change point.

Barry and Hartigan (1993) proposed a Bayesian change-point algorithm which assumes that from a sequence of n independent random variables there is an underlying sequence of parameters partitioned into contiguous blocks of equal parameter values. The beginning of each block is called a change-point. We used an R implementation of the Barry and Hartigan (1993) product partition model for the standard change-point problem using Markov Chain Monte Carlo (MCMC) implementation (Erdman and Emerson 2007).

Step 3: Estimation of the monthly center of gravity of each indicator within each homogeneous block of years

From step 2 we assumed that each homogeneous time period of each indicator (representing a strategy) are characterized by uniques spatio-temporal strata (tactics). To determine the time-space strata size, we estimated the center of gravity (CG) of each indicator at given coordinates for each month within a homogeneous block of years. The CG concept comes from particle mechanics systems, and it is the point where all the weight of a collection of masses can be considered to be concentrated, i.e., the mean location of the masses that compose a system of particles (Greiner 2010). Let a system consist in n particles with the position vector $\mathbf{r}_v$ and the masses m_v for $v = (1,\ldots, n)$. The CG of this system is defined as point S with the position vector $\mathbf{r}_S$.

$$\mathrm{r}_S = \frac{1}{M}\sum_{v=1}^{n} m_v \mathrm{r}_v$$

Where M is the total mass of the system ($\sum_{v=1}^{n} m_v$) and $\sum_{v=1}^{n} m_v \mathrm{r}_v$ is the mass moment.

The CG has been used as a spatial indicator in ecological applications. In such case the moment of mass is replaced by the density of the population in a two-dimensional space and the total mass is replaced by the total abundance of the population (Bez and Rivoirard 2000; Woillez et al. 2007). For each indicator ($JuvC^+$ and *FrSc*) the value at its corresponding coordinates reported in logbooks of the French purse seiners was used replacing the population density, and the sum of the values as the total abundance of the population.

Step 4: Chronological clustering of monthly centers of gravity

Time-constrained clustering consists in introducing a constraint of temporal contiguity (i.e. ensuring that only neighboring spatial units or consecutive temporal units are grouped) in the clustering process to identify discontinuities in multispecies time series (Legendre and Legendre 1998). Theoretically, from a dissimilarity matrix between the time units, chronological clustering could be applied either in a temporal or in a spatial sequence. However, Borcard et al. (2011) suggested that with the use of a multivariate regression trees (MRT; De'ath 2002), chronological clustering may be applied to both spatial and temporal contexts.

MRT is an extension of univariate regression trees, a method allowing the recursive partitioning of a quantitative variable under the control of a set of quantitative or categorical explanatory variables. MRT consists in two procedures running together: (1) constrained partitioning of the data with the aim to produce all possible partitions of the sites into two groups, then repeating the procedure for each new subgroup generated and minimizing the sums of squared distances within-group, and (2) a cross-validation of the partitions and pruning the tree (generally with the one standard error rule) to establish the number of terminal nodes of the final tree.

To implement this, it is suggested using a vector representing the temporal contiguity as the only explanatory variable. In this study, we used the cumulative distance of the monthly CGs of each block of years as the constraint of temporal contiguity and the geographical coordinates of the monthly CGs as the response variables. The cumulative distance of CGs avoids clustering two months close in space but chronologically far apart.

Step 5: Intensity of each indicator according to the clusters identified in each homogeneous block of years

To determine the spatial extent of the two indicators ($JuvC^+$ and *FrSc*) tactics resulting from the chronological clustering defined in step 4, a spatial point pattern analysis was used. A point process (PP) is a stochastic process in which the locations of some events of interest are observed within a bounded region. For the sake of simplicity a Poisson process was used because it offers a more flexible approach to a wide range of problems (Bivand et al. 2008). Because the clusters resulting from step 4 imply different strata in time and space we assumed that the PP of each cluster was inhomogeneous. From this assumption intensity was estimated by a nonparametric method, which is carried out by means of kernel smoothing using an isotropic Gaussian kernel.

For n points, $\{x_i\}_{i=1}^{n}$ the form of a kernel smoothing estimator may be expressed as follow (Diggle 1985):

$$\hat{\lambda}(x) = \frac{1}{h^2}\sum_{i=1}^{n}\kappa\left(\frac{\left\|x - x_i\right\|}{h}\right) / \, q(\left\|x\right\|)$$

where $\kappa(u)$ is a bivariate symmetrical kernel function. $q(\|x\|)$ represents a border correction to compensate for missing observations that occur when x is close to the border region. The bandwidth h measures the level of smoothing. In this step the analysis was made using an R implementation for analyzing spatial point patterns in the package spatstat (Baddeley and Turner 2005).

2.3 Results

2.3.1 Regime shifts in tuna purse seine strategies

Regime shifts in the strategies of the French tropical purse seine fishery were detected based on each fishery indicator series that showed major and sudden changes during 1981-2008, concomitantly with the introduction of new fishing devices. From BCP analysis, the number of sets on free-swimming schools per day was characterized by an increasing trend over time marked by 2 upward shifts in 1988 and 2002 (**Figure 2.4 - left column**).

Catches of juveniles on FADs per day also resulted in three distinct time periods, with transition years estimated to be 1991 and 1996, respectively (**Figure 2.4 - right column**). From less than 2 $t.d^{-1}$ during the first period (1981-1991), catches increased between 8 and 12 $t.\ d^{-1}$ in the second period (1992-1996). It should be stressed that at the beginning of this period a massive increase in the use and deployment of FADs at-sea was observed. A major decrease in catch rates of juveniles of tunas was then observed in 1997 (**Figure 2.4d**). From this year, the voluntary-based moratorium on FAD-fishing was implemented, and then it was adopted by ICCAT. Details on the relationship of the technology introduced with regards to each fishing mode are given in the discussion section of this chapter.

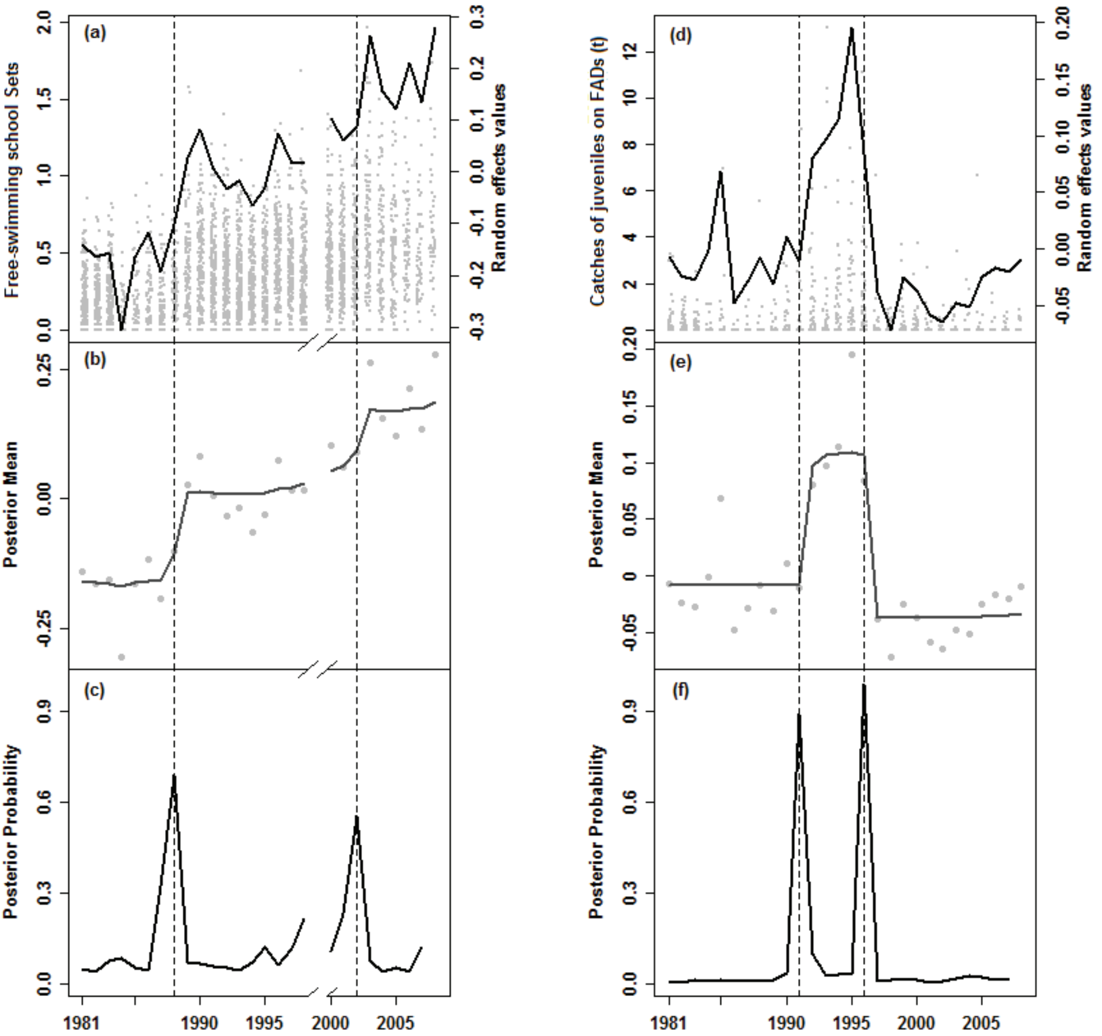

Figure 2.4 Bayesian change-point analysis of the number of free-swimming school sets per day (left column) and catches of juveniles on FADs per day (right column). Observed values (dots, left y-axis) and resulting yearly random-effect values (black line, right y-axis) are represented in the upper part of the figure. The posterior mean is in the middle part. The posterior probability of a shift in mean value (i.e., the proportion of iterations resulting in a change-point for each year) is represented in the lower part.

2.3.2 Seasonality in tuna purse seine strategies

Seasonal changes (tactics) on free-swimming school fishing strategy were less marked than for FAD-associated schools strategy, i.e. the fishing tactics were consistent over time. Month grouping based on the number of sets on free-swimming schools did not yield any noticeable change among the homogeneous periods of years (**Figure 2.5 - upper part**). Over the three time periods was evidenced there remained three seasons, usually with variations of no more than one month long. The longest season corresponded from early autumn to late winter (**Figure 2.5 - upper part**). The second season usually corresponded to the spring months, and the third always started in June and ended in September or October (**Figure 2.5 - upper part**).

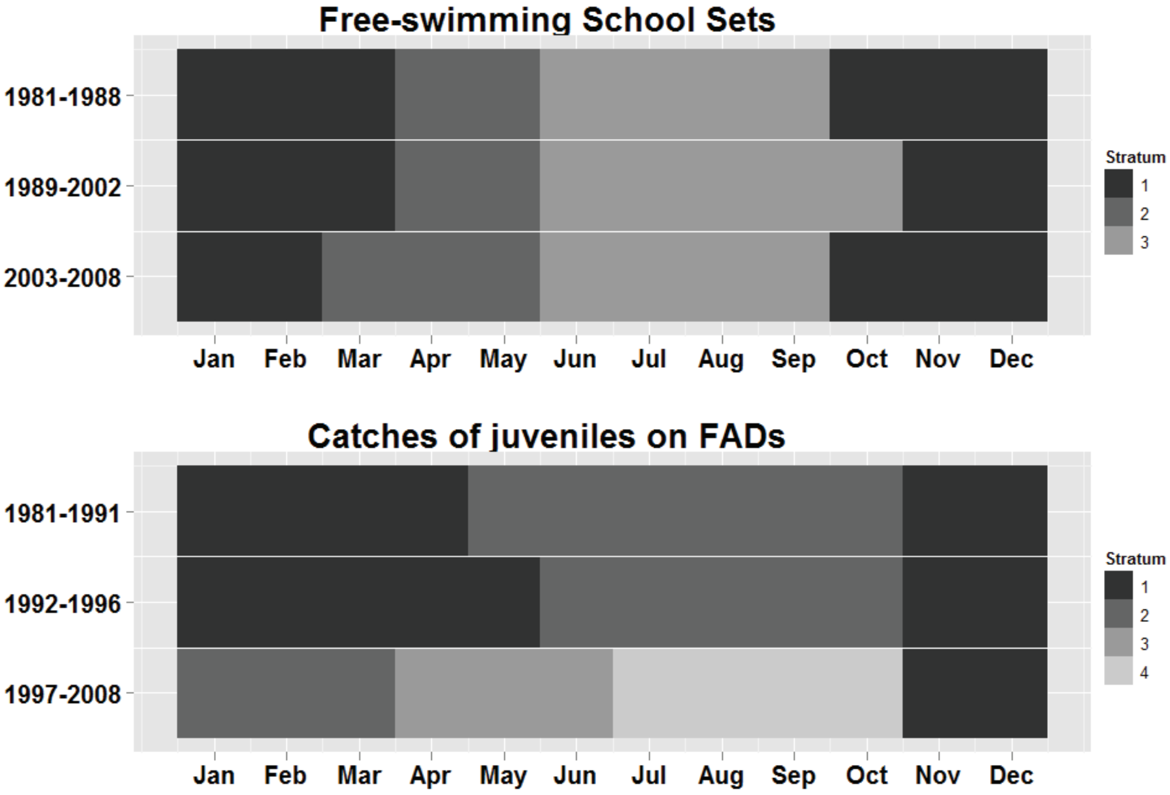

Figure 2.5 Seasons evidenced from chronological clustering for number of sets on free-swimming schools per day (upper part) and catches of juveniles on FADs per day (lower part).

In contrast to that was observed for free school strategy, FAD-fishing showed marked changes in tactics over time (i.e. marked seasonality). From chronological clustering it was showed changes in the grouping of the months within each homogeneous period of years (**Figure 2.5 - bottom part**). During the first period (1981-1991) there were two main temporal strata characterizing catches of juveniles on FADs: November-April and May-October (**Figure 2.5 - bottom part**). In the second period these two predominant seasons yielded moderate changes: November-May (i.e., one month later than in the previous period), and June-October (**Figure 2.5 - bottom part**). Over the third period however, four distinct temporal strata were obtained by the clustering analysis: (1) November and December, (2) from January to March, (3) from April to June, and (4) from July to October (**Figure 2.5 - bottom part**).

2.3.3 Spatial variations in purse seine fishing tactics

The number of sets on free-swimming schools did not yield major spatial changes but indicated strong variations in magnitude over the period 1981-2008. From 1981 to 1988 the highest concentration of free-swimming school strategy was in the Picolo area from October to March; the extent of this tactic encompassed part of N. Equator and part of S. Equator below Picolo (**Figure 2.6a**). Then, from April to May, this high spot moved to a region between Senegal and NW Picolo areas (**Figure 2.6b**). The third temporal stratum (June-September) yielded three coastal concentrations: Cap Lopez (the highest), N. Equator, and Senegal (**Figure 2.6c**). In the period 1989-2002, from November to March there was an expansion on the area covered by this fishing strategy, encompassing Picolo, N. Equator, S. Equator and a small part of NW Picolo, where the highest concentration was located along the equator (**Figure 2.6d**). The second temporal stratum (April to May) was observed in the same region as in the previous time-period (1981-1988), with the highest concentration observed between Senegal and NW Picolo areas (**Figure 2.6e**). In the third temporal stratum (June to October) the highest concentration was located in the Cap Lopez area, N. Equator and, to a lesser extent, in the Senegal region (**Figure 2.6f**). In the most recent period (2003-2008) during the first two temporal strata identified (October-February and March-May), the spatial extent of the free-swimming schools strategy remained in the same areas as in the previous years (**Figure 2.6g-h**). From July to September (third temporal strata) the extent of the area was reduced to N. Equator and Cap Lopez (**Figure 2.6i**).

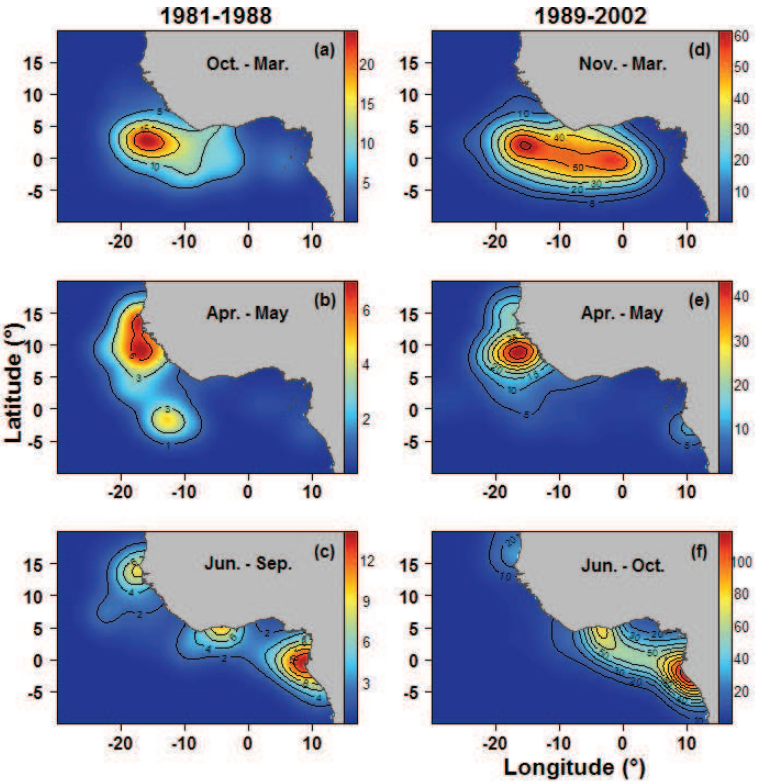

Figure 2.6 Spatial extent of the number of sets on free-swimming schools for the seasons found within each homogeneous period of years (1981-1988 left column, 1989-2002 middle column, and 2003-2008 right column).

Major spatial changes occurred in FAD-fishing tactics, both between and among the yearly time periods delineated over the period 1981-2008. In the first temporal stratum of the first period (i.e., November to April, 1981-1991), catches were mainly located in the Picolo area (**Figure 2.7a**) while the highest concentration in the second temporal stratum (May-October) was found in the Cap Lopez area (**Figure 2.7b**). During the second period (1992-1996), the purse seine fishery expanded across the Gulf of Guinea (**Figure 2.7 - middle column**). The first temporal stratum (November-May) encompassed the Picolo area, NW Picolo, N. Equator, and S. Equator (**Figure

2.7c). The highest concentration was located in the region between Picolo and N. Equator areas. That second temporal stratum (June-October) of 1992-1996 was similar to the second described during the 1981-1991 period, but resulted in an expansion into the Gulf of Guinea encompassing the Cap Lopez area, N. Equator (highest concentration for that stratum) and part of S. Equator (**Figure 2.7d**). In the last period (1997-2008), the areas presented before were spatially disaggregated (**Figure 2.7 - right column**). For instance, during the first temporal stratum (November-December) juvenile catches on FADs decreased and were concentrated in a small region within the NW Picolo area (**Figure 2.7e**). From January to March (second temporal stratum) there were three spots: NW Picolo with the highest concentration, inside the N. Equator, and into the north of the Cap Lopez area (**Figure 2.7f**). From April to June the spot with the highest concentration was located in the Senegal area, followed by other spots (**Figure 2.7g**). The last temporal stratum (July to October) remained similar to the pattern observed during the second stratum of the two previous time periods, with locations in the Gulf of Guinea encompassing N. Equator, Cap Lopez and part of S. Equator but with a lower concentration (**Figure 2.7h**).

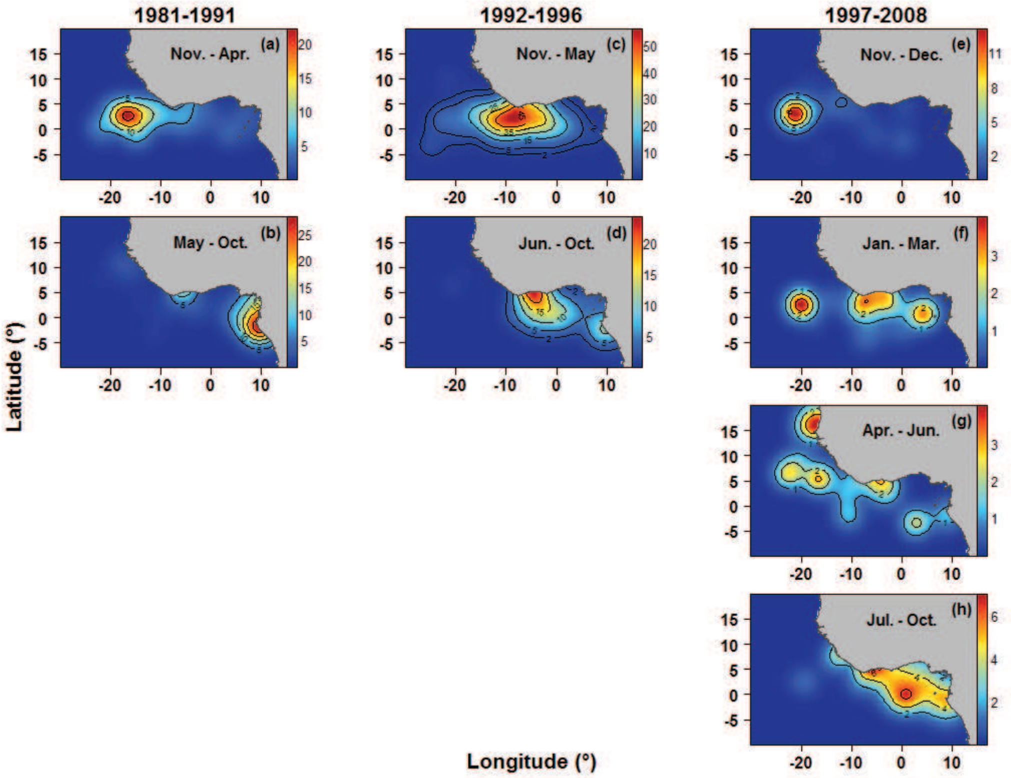

Figure 2.7 Spatial extent of the catches of juveniles on FADs for the seasons found within each homogeneous period of years (1981-1991 left column, 1992-1996 middle column, and 1997-2008 right column).

2.4 Discussion

The trends and patterns in the strategies of the French tropical tuna purse seine fleet were described and analyzed across multiple temporal and spatial scales and related to auxiliary information on the improvement of vessel and gear attributes. On a decadal time-scale, the results showed major shifts in the indicator time series for both fishing strategies. Changes in catches of juveniles of tunas were mostly explained by the introduction of FAD-fishing from the early 1990s and the implementation of time-area regulatory measures by ICCAT. Meanwhile, the increasing trend in the daily number of sets made on free-swimming schools was assumed to be mainly related to improvements in attributes dedicated to school detection. These results revealed that large yellowfin fishing grounds have been consistent across temporal strata (tactics) over the last 3 decades despite steady improvements in vessel fishing power and a concomitant decrease in stock biomass. By contrast, FAD-fishing has been characterized by marked temporal strata changes over time associated with an initial expansion toward the west in the mid-1990s followed by a fragmentation of the fishing grounds in the 2000s.

2.4.1 Monitoring technology in fisheries

Considering the extent of their fishing grounds, spatio-temporal distribution of tropical tunas is characterized by patchy schools gathering into concentrations (Fonteneau 1989; Ravier et al. 2000; Fonteneau et al. 2008). Therefore, adopting fishing devices for locating and efficiently exploiting the ephemeral patches of tuna schools appears as a necessity to maintain this type of fishery at an economically sustainable level (Gaertner et al. 1999). Minimizing the number of fishing days without catch and reducing the rate of unsuccessful sets (i.e., using a FAD-fishing strategy) have indeed been revealed as economically beneficial for this type of fishery. In large part, fishing will provide knowledge, which will in turn generate experience, and all this will define where and when to fish. One way of achieving this goal consists in investing in fishing technology. Through the introduction of new fishing devices it is possible to access new fishing grounds and acquire more independence at sea in order to be more efficient in the fishing grounds that are already known and to target commercial species/size categories of higher economic value. However, the rate of investment in a fishery depends on the level of its development and this may lead to overcapitalization. Fishermen strategies and tactics are essential elements in fisheries assessment (Salas and Gaertner 2004; Branch et al. 2006) and analyzing investment and its consequences contributes to understanding the behavior of the fleets (Hilborn and Walters 1992). Information on capital investment and technological use is however confidential and not available to scientists as it can provide a crucial advantage to fishing companies for the exploitation of fish resources. Here was collected a large set of qualitative and original information on the dates of technology introduction on board the French purse seine fleet over the last 3 decades. A summary of the main technological innovations linked with changes in fishing strategies and their potential effects on tropical tunas is provided in the following subsections (for details about the census of introduction of technology see Gaertner and Pallarés 2002).

For this analysis, as mentioned earlier, we did not consider the Spanish purse seine fleet because the introduction of new technology on board the Spanish fleet was likely done at different years, owing to different fishing strategies with the French fleet. Consequently this could lead to a misunderstanding of the effects caused on the fishery indicators. It should be stressed that Spanish fishermen's remuneration system is based on total catch while French crews are remunerated according to the value of the catch (i.e. higher sale price for large tunas). Therefore, FAD-fishing operations with the assistance of supply vessels predominate in the Spanish fleet while the proportion of risky, but valuable, free-swimming school sets on large yellowfin remains high for the French purse seiners.

2.4.2 CPUE in tuna purse seine fisheries

Untangling the effects of spatio-temporal variations in fish abundance and on-board technology is challenging because abundance indices for tuna stocks are mostly derived from fishery-dependent information, i.e. commercial CPUE. This has been a major impediment for the use of purse seine CPUEs in assessing the stock status of tropical tunas which are mostly based on abundance indices derived from commercial Asian longline fisheries. In the present analysis we assumed that changes observed in the fishing strategies of the French purse seine fishery since the early 1980s were mainly driven by technological improvements. However, these changes could be affected by variations in tuna abundance and/or environmental variability. Regarding the tuna abundance, the 3 main tropical tuna species have experienced increasing fishing pressure since the 1960s in the Atlantic Ocean which has resulted in a steady decrease in their total and spawning stock biomass over time (ICCAT 2010, 2011a, b). Meanwhile no declining trend was observed in the CPUE time series of purse seiners for large tunas (Pianet et al. 2011) while our results showed that the daily number of sets on free-swimming schools (*FrSc*) increase over time. Similarly it is admitted that time series of recruitment estimates available for yellowfin and bigeye showed inter-annual variability without any trend until the late 1990s (ICCAT 2011a, b) while CPUEs for FAD-fishing including skipjack increased during this period. The recruitment of the eastern Atlantic skipjack is unknown, but the most recent management status indicates that there is no evidence that the stock has been overfished (ICCAT 2010). Hence, yearly time series of purse seine CPUEs in the eastern Atlantic do not seem driven by variations in abundance which suggests that the results are conservative and that effects of increased fishing power may be more pronounced than showed here, i.e. they compensate for the decrease in abundance while resulting in increased catch rates over time.

As mentioned above, changes in environmental conditions may affect the distribution of tuna abundance and could explain to some extent the spatio-temporal patterns observed. The tropical Atlantic Ocean, as explained in Chapter 1, has marked seasonality but low interannual variability (Hardman-Mountford and McGlade 2003) compared to the Pacific Ocean for instance. Except for 1984 (Binet and Marchal 1993), no major environmental signal has been observed in the eastern Atlantic during the last decades (Hardman-Mountford and McGlade 2003). Thereby, the regime shifts in the fishery indicators observed on a decadal scale do not seem to be related to particular environmental conditions. If an environmental phenomenon would affected the fishery indicators it would be characterized by a rapidly increase followed by an immediate return to a previous state, not observed in our results, where the change was characterized by a series of steady values in each period of years (i.e., an homogeneous time period).

2.4.3 Changes in efficiency and fishing strategies linked to the introduction of new technology

Defining the effective fishing effort in purse seine fisheries has always been a difficult task. This issue is particularly important due to the fact that purse seine fishery is a multispecies fishery in which there are two different fishing strategies (free-swimming schools and FAD-fishing). Free swimming schools catch rates are defined as the quantity of fish caught in a set divided by the searching time preceding it. Searching time corresponds to the daylight hours spent on the fishing grounds minus (1) the time spent during unsuitable events (bad weather, etc.) and (2) the time spent chasing and setting. Accordingly, good estimates of these amounts of time are necessary to obtain correct interpretation of the relationship between catch rates and abundance index (Gaertner et al. 1999). In FAD-fishing effective effort has particularly been difficult to estimate, since it is unknown the number of FADs deployed by vessel or for instance, the distance between them. For this reason defining a unique estimator of the effective fishing effort is unrealistic, notwithstanding it is important to better understand the way in which the introduction of new technology improves the fishing efficiency and changes the fishing strategies. As also reported for tuna longline fisheries (Ward and Hindmarsh 2007; Ward 2008), there have been major introductions of technology on board tuna purse seiners during the last 30 years, which have resulted in increased fishing efficiency and fish catchability (Fonteneau et al. 1999). Observing concomitant changes in the main two fishing strategies of the purse seine fishery in the eastern tropical Atlantic, with the chronological introduction of new fishing devices provides an insight into fishermen behavior at sea. As mentioned previously, some studies have analyzed the effects of the use of new technology by the European tropical tuna purse seine fishery in the eastern Atlantic. The analyses dealt with fishing efficiency (Pallarés et al. 2001), with the effect of the purse seine size (Gaertner and Sacchi 2000; Santana et al. 2002), with the use of the sonars (Gaertner et al. 2000), and supply vessels (Pallarés et al. 2002). In the case of the present study changes over time of the indicators are more related with the concomitant and combined effects of different devices introduced approximately at the same dates.

The first regime shift observed on free-swimming school fishing in 1988 coincides with the introduction of: (1) sonars scanning 360°, where the main role of these devices is to help in the decision process before setting on a school. They allow skippers to evaluate the school size and their displacement (Gaertner et al. 2000). (2) Bird radars with 30 kW output power, may be directly related with an increase in the effective searching area, which is more related to free-swimming schools. By using bird radars, skippers can plot the displacements of bird flocks and measure their speed and in such a way obtaining relevant clues for the detection of tuna schools at the surface of the sea. Later, more powerful sonars (e.g. tracking sonar and low frequency sonar) and bird radars (e.g. 60 kW, ARPA, 65 kW) were introduced, however in that time, the introduction of these new devices resulted in a prominent improvement of the fishing power. Another technological improvement of the late 1980s concerns the setting process. Before 1985, French seiners were equipped with closing roller purse rings. Consequently removing the roller purse rings from the purse line was slow and dangerous. From 1985 and for nearly four years the French seiners adopted the opening roller purse rings. This improvement resulted in faster sets, an important fact to avoid the school escaping from net-setting and to decrease the part of daytime unspent on searching.

The second regime shift observed may be related with the generalization of current meters and some new vessels with two sonars. This assumption is based on the fact that, as strong currents may deter skippers from attempting a risky setting, using a current meter enables them to know the strength and the direction of the current at different depths. In addition, satellite maps introduced between 2000 and 2003 provide skippers with information about oceanographic conditions, facilitating find suitable areas for tuna schools. The introduction of these devices, in addition to those introduced in the late 1980s, and the experience gain may lead to the slight increase observed in the number of sets on free-swimming schools per day, suggesting that vessels increased their fishing power. Considering the changes in the time series of this indicator the use of new technology introduced had direct effects on the efficiency of the vessels, but it did not affect their temporal tactics since all three periods had three temporal strata of almost the same length.

Early in the fishery, setting on natural objects was incidental, seldom reported in logbooks (Ariz et al. 1993) and restricted to certain areas and seasons (Cayré et al. 1993). The introduction of FADs in the late 1980s and early 1990s may be the most relevant technological innovation in tropical tuna surface fishing in the last 30 years (Ariz et al. 1993; Delgado de Molina et al. 1999; Miyake 2005). After their generalization in the early 1990s advances has been uninterrupted with (1) the implementation of GPS positioning buoys (1997-1998), particularly of the Ariane type, which progressively substituted the Gonio system introduced in the early 1990s, and (2) satellite tracked buoys (in the early 2000s) that transmit continuous buoy trajectories to a computer interface on board the vessel and sonar-transmitting satellite buoys, equipped with solar panels, which became very useful for optimizing time spent traveling to and assessing FADs (Itano 2003). These fishing methods depend upon different skills. For instance fishing on free-swimming schools is more like hunting (yielding catch with the highest commercial value but unsuccessful set can occur), whereas fishing on FADs is like sowing and harvesting (small tuna are less valuable but the rate of unsuccessful sets is low; < 10%). It was recently showed for the European tropical tuna purse seine fishery of the Indian Ocean, that FAD-fishing strategy is often related to the growing carrying capacity characterized by larger vessels, better-equipped buoys, echo-sounders, and supply vessels (Guillotreau et al. 2011).

While the main cause of the increase in catch of juveniles was due to the intensification of FAD-fishing other factors could also have contributed to this trend. It is commonly accepted that bigeye tuna occupies the deepest part of a multispecies school. Hence deeper purse seine may have increased its vulnerability to FADs (Gaertner and Sacchi 2000). These authors reported an increase in seine sizes in the 1970-2000 period associated with the development of more powerful hydraulic equipment (e.g. winches and power blocks) related with the turning and the lifting of the seine. Until 1988 purse seine depth was 185 m, became deeper at the beginning of the 1990s (210 m) and in the late 1990s most vessels used purse seines that were between 210-240 m depth. There are, however, limitations on the size of the net and advances are found now in the net materiel allowing a faster penetration of the purse seine in the water during the setting. Once FADs were introduced, skippers were able to decide to fish on free-swimming schools or on FADs. Consequently the impact was not only in terms of fishing power but also in terms of new fishing tactics (including new fishing areas and/or changing temporal strata length). This mixture of fishing modes and fishing zones would be interpreted as a series of tactics resulting in different fishing strategies. However, in this study it was preferred define fishing on free-swimming schools and fishing on logs as two fishing strategies to taking into account the introduction of new technology in the 1980s, otherwise it should be carried out the analysis since the development of FAD-fishing in the early 1990s. The latter may lead to missing relevant information about spatio-temporal strata on both fishing modes during the 1980s.

Considering the sudden decrease in the catches of juveniles (at least for the French fleet) in 1997, it may be noted that it coincided with the entry into force of the moratorium on FAD-fishing. As a consequence of the moratorium there were reductions in annual landings of the three species of tropical tunas (Ariz et al. 2005, 2009). The analysis of the effects of the time-space regulatory measures is carried out in Chapter 3. Thus, despite the continuous investment in fishing technology there was no increase in catches of juveniles. With respect to the increase in juvenile catches in the early 1990s it makes sense to assume that the causes were the introduction of FADs which increased the fleet’s fishing efficiency and the resulting extended spatio-temporal tactics beyond the Gulf of Guinea. But, among the different factors analyzed the predominant one that modified previous seasonal patterns was the time-space regulation.

2.5 Conclusions

Times series of CPUE provide critical information to population dynamics models to reconstruct past trends in fish stock abundance. However, in tropical tuna purse seine fisheries the constant improvement of vessel and gear attributes, combined with a mixture of fishing on unassociated and FAD-associated schools, hinder the use of fishing/searching time as a pertinent measure of effort. This issue is common challenge among Tuna-RFMOs because the lack of non-commercial estimate of abundance and also concerns the other fishing gears characterized by increased fishing power as well as major changes in strategies and tactics. This is the case in pole-and-line fisheries through the associated-school fishing method developed in Senegal (Fonteneau and Diouf 1994; Hallier and Delgado 2000) or in other oceans the use of anchored FADs (Langley et al. 2010; Kolody and Adam 2011) and in longline fisheries by a direct improvement of the fishing gear (Ward 2008). As showed in this chapter, technology has depicted a direct effect modifying the fishing efficiency in each strategy and an indirect one by allowing new range of spatio-temporal tactics. Accessing past and current information on technology (i.e., capital and equipment), through a close collaboration with the fishing industry, would also contribute to improve our understanding of changes in fishing power and strategies on catch rates. In addition to qualitative information on dates of introduction of technology, French tuna fishing companies, regrouped under the ORTHONGEL association, have begun to provide FAD trajectories information with scientists at the national level. Furthermore, electronic logbook systems on board purse seiners, that should become operational by the end of 2012, will include information on FAD operations, i.e. deployment, visit, and buoy transfer. This information may be included to evaluate the mixture of fishing grounds and alternating between fishing modes.

Chapter 3

Adaptive responses of fishermen facing regulatory measures

3.1 Effects of time-area closures on tropical tuna purse-seine fleet dynamics through some fishery indicators[1]

3.1.1 Introduction

In the previous chapter, it was observed how the time-area regulatory measures affected the fishing strategies and the fishing power of the French purse seine fleet. Together with the above, within the framework of fisheries management introduced in Chapter 1, seasonal area closure has been used by managers to protect harvested species in mature fisheries (Branch et al. 2006; Agardy et al. 2011). However, this management tool is more likely to be effective when species have moderate mobility than for highly mobile species (Hilborn et al. 2004; Harley and Suter 2007; Jensen et al. 2010). For instance it was suggested from simulation studies that to obtain some benefits for highly mobile species, a very large closure area (as large as 85% of the total area of the stock) may be required (Le Quesne and Codling 2008). In this section will be addressed the effects of the two time-area closures, described in Chapter 1, on the fleet dynamics of the European (EU) purse seiners operating in the eastern Atlantic Ocean.

Summing up, in the mid-1990s the ICCAT requested further analysis to determine protected fishing areas and seasons due to the large increase in the catches of bigeye tuna and juveniles since the early 1990s. The ICCAT adopted and extended in 1999 to all fleets operating in the Atlantic Ocean a voluntary moratorium on FADs carried out by EU boat owner companies since 1997. Then, this moratorium on FADs was replaced by resizing the area and reducing the period of the former regulation from 2005.

Different studies have evaluated the effects of these spatial regulations on the catches (Diouf et al. 1999; Goujon and Labaisse-Bodilis 2000; Ariz et al. 2001; Goujon 2004a; Goujon 2004b; Ariz et al. 2005; Cass-Calay et al. 2006; Brooks and Mosqueira 2006; Ariz et al. 2009; De Bruyn and Murua 2010). However, no document has been devoted to the consequences of the establishment of a spatial regulation on purse seiner fleet behavior at sea. Even if the idea of implementing a spatial regulation is to protect the harvested species, it will affect the users in some way, and thus it is necessary take into account the fleet response to improve the fishery management (Johannes et al. 2000; Wilen et al. 2002; Salas and Gaertner 2004; Kaiser 2005; Branch et al. 2006; Poos and Rijnsdorp 2007). For this reason and according to the scope of this dissertation manuscript, the aim of this section is to evaluate the effects of the two spatial regulations on the purse seiner fleet behavior using different fishery indicators.

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[1] This section corresponds to the following publication: Torres-Irineo, E., Gaertner, D., Delgado de Molina, A., and Ariz, J. 2011. Effects of time-area closure on tropical tuna purse-seine fleet dynamics through some fishery indicators. Aquat. Living Resour. **24**: 337-350. doi: 10.1051/alr/2011143.

3.1.2 Material and Methods

3.1.2.1 Data

The analysis is based on logbook data reported by EU purse seiners (France, Spain, and associated flags) described in Chapter 2. For the moratorium on FADs period (1) an increment is expected in the activities on free-swimming schools both inside and outside the moratorium on FADs area (**Figure 1.9**), whereas (2) for FADs activities there should be an increment outside moratorium area. On the other hand, the fishery indicators, except those on free-swimming school, are expected to decrease inside the area (e.g., days with catch) once the moratorium entered into force. Regarding the no-take recommendation [04-01], a total reallocation of the surface fishing effort is expected and, as a consequence, a rise in fishing activities outside the area during the month of November on both free-swimming schools sets and FADs sets as well as the corresponding catches. A summary of the characteristics of each regulation is presented in **Table 3.1**.

Table 3.1 Main characteristics of the two management measures adopted by ICCAT for tropical tunas.

Measure	Moratorium on FADs	No-take closure
Years	1997-2005	2005-2010
Months	November-January	November
Area	4°S-5°N and 20°W and the African coast	5°N and Equator 0° and 10°W to 20°W (Picolo Zone)
Restrictions	Fishing on FADs	All surface fishing gears

To analyze the activity of the EU purse seine fleet and to estimate whether the fleet dynamics changed as a consequence of the two management measures, different indicators were used on a monthly basis:

- the total number of days with catch (Dy^+) and the number of 1° x 1° squares explored successfully (Sq^+) representing the success of the fleet in terms of catch independently of the fishing method used, and the fishing time (*FT*) representing the time spent by the fleet in the zone, i.e. time at sea;
- the number of sets on free-swimming schools (*FrSc*), was used to detect whether there was an increase in the effort associated with this fishing mode due to the interdiction on FADs, and the number of sets on FADs (*FAD*), assumed to represent directly the effects of the regulation measures (as mentioned previously the aim of the regulation on FADs was to reduce the catch of juveniles). These two indicators were considering positive sets and unsuccessful sets, i.e., without catch;
- catch with FADs ($FadC^+$), catch of juveniles with FADs ($JuvC^+$) and catch of large yellowfin tuna on free-swimming schools (YFT^+) are the result of the fishing modes selected by fishermen (Table 3.2).

Fishery indicators were performed for the two periods considered (1995-2005 and 2000-2008). With the aim of pointing out a contrast between before and after the corresponding spatial regulation, the first period was divided from 1995 to 1997 (before) and from 1997 to 2005 (after) and the second period from 2000 to 2004 (before) and from 2005 to 2008 (after). Not all the vessels operated in both periods of time. Consequently, to ensure that the results represent the effects of each regulation, only vessels with at least 50% of presence in each period were considered. This supposes that these vessels would have more knowledge about spatial and temporal strata. Furthermore, some vessels operated only before or after each regulation, and in this case the information supplied by them did not take into account the effects of the regulations. Thus, the indicators were calculated on the basis on information provided by 33 and 25 vessels for the first and the second period, respectively. For the comparison purpose the indicators were normalized (i.e., averaged) per vessel per month.

3.1.2.2 Method

Assessing a change over time on a system is termed as impact assessment. This approach aims to evaluate (1) whether or not a stress has changed the environment, (2) to determine which components are adversely affected, and (3) to estimate the magnitude of the effects. Theoretically, when information is available prior to the potential impact, the design is often referred to as a Before-After Control-Impact (BACI) design (Smith 2002). In addition, when historical data are available it is possible to estimate the effects of an impact, and considering the presence of a control zone (i.e. not impacted) will improve the estimation of such an impact (Eberhardt and Thomas 1991; Wiens and Keith 1995).

Data prior to an impact are normally difficult to obtain for evaluating its effect on most biological resources (Wiens and Keith 1995; Smith 2002). When historical data are available for the impact area it is possible to compare means for samples from these data and periods after the event. If there is no such effect it is expected that these means are equal and if not, a statistical difference is taken as evidence of effect (Underwood 1992; Wiens and Keith 1995; Smith 2002). This approach is called Before-After design (BA) which is without control locations to compare, and consequently the observed changes could be due to causes other than the impact (Smith 2002). When conducting this design it is assumed that the other factors besides the impact affecting a resource are homogenous during the whole period.

The statistical model for the analysis of data, X_{ik} is

$$X_{ik} = \mu + \alpha_i + \tau_{k(i)} \quad (1)$$

where μ is the overall mean, α_i is the effect of period (i = before or after), and $\tau_{k(i)}$ represents times within i period ($k = 1, 2, \ldots, t_A$, for i = after and $k = 1, 2, \ldots, t_B$ for i = before).

A variation of the above design is to sample more than one location in the impacted area, and it is suggested that some control locations be added to compare with the impacted area (Underwood 1992; Smith et al. 1993; Wiens and Keith 1995; Smith 2002).

In our analysis, since the moratorium region might suffer changes outside as well as inside for many reasons (e.g., changes in fishing effort over the years) it was difficult to define a control zone. Consequently, the assessment of the effects on the purse seine fleet dynamics was conducted by a BA design. The statistical model for this analysis was the same as in equation (1).

The analysis was carried out using ANOVA when the indicator data satisfy the assumptions of normality and homoscedasticity, or a Kruskal-Wallis test when assumptions were violated. The data were divided inside and outside depending on the regulation measure and coded to differentiate the before and after period, permitting taking replicated samples at repeated times because each year the impacted area was sampled by the vessels. The inside-outside interaction was difficult to interpret and to evaluate, thus to determine if there was an effect outside of the area the same analysis was carried out with the corresponding data.

It should be notice that before the entry into force of the no-take regulation there was already an effect from the moratorium on FADs. To attempt to mitigate this effect the years 2000-2004 were considered as the period before the no-take closure, because from 2000 all fleets had to comply with the moratorium on FADs and thus it was assumed that normal conditions were the moratorium.

In addition to the BACI approach, descriptive analyses were done to show the spatial distribution of the number of sets in both fishing strategies (free-swimming schools and FADs) before and after the spatial regulations.

3.1.3 Results

3.1.3.1 Moratorium on FADs

3.1.3.1.1 Fishing activities before and after the moratorium on FADs

Before the implementation of the moratorium on FADs (1995-1997) and for the three-month period (November-January), each EU vessel carried out on average more fishing activities within the moratorium area than outside (**Table 3.2, Figure 3.1**). Only activities related with free-swimming schools had similar values throughout the time series. It must be stressed that within the protected area in November and December there were more sets on FADs than on free-swimming schools (**Figure 3.3e, 3.3f**). Nevertheless, there was an increase in the number of sets on free-swimming schools in January (**Figure 3.3f**), while sets on FADs decreased, mainly inside the FADs moratorium area in the same months period (**Figure 3.3e**). Therefore, catches associated with each fishing method followed the same trend (**Figure 3.3g, 3.3h**). This pattern was similar for the catches of juveniles (< 1.8 Kg) during November-December 1995 and 1996 where the catches were the highest (**Figure 3.1h and Figure 3.3d**). On the other hand, inside the moratorium on FADs zone the numbers of days with catch (Dy^{+}), the numbers of squares visited with catch (Sq^{+}), and the fishing time (FT) remained with high values before the voluntary ban on FAD-fishing entered into force (**Figure 3.1a, 3.1b and 3.1c**, respectively).

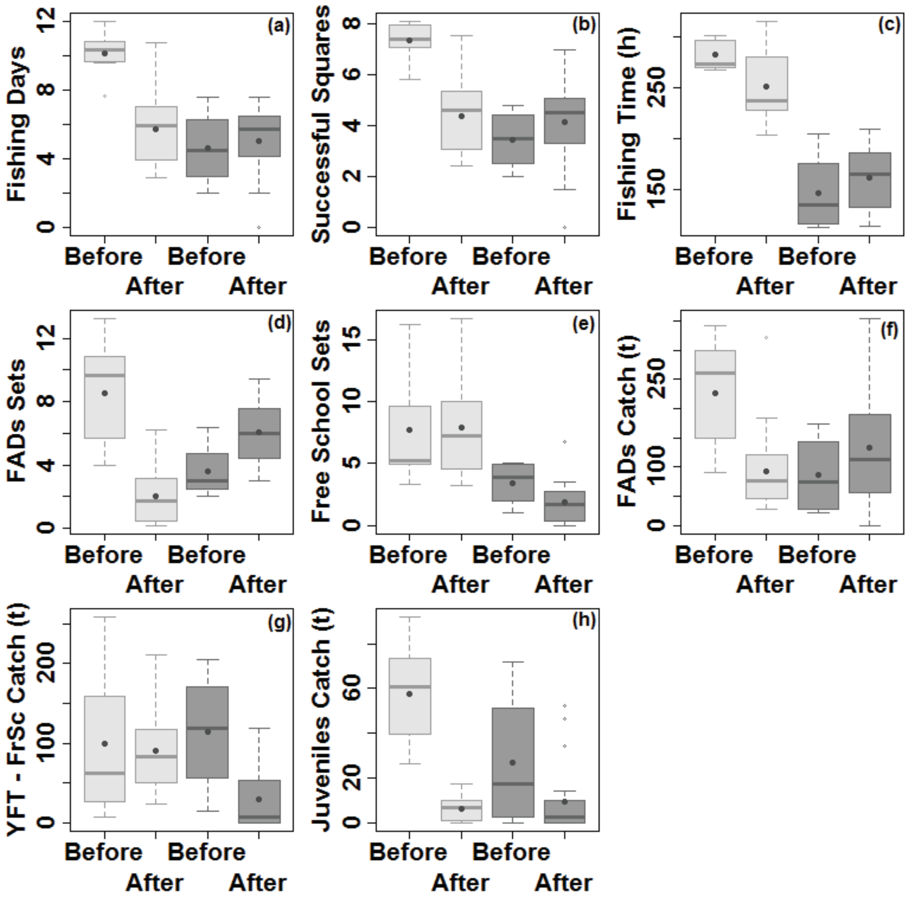

Figure 3.1 Fishery indicators box-plot inside (light gray) and outside (dark gray) the moratorium on FADs area for the three-month period before (1995-1997) and after (1997- 2005). The average and the median are represented by points and stripes, respectively.

Once the voluntary moratorium on FADs followed by the ICCAT regulation was implemented, there were some changes in the patterns of the indicators analyzed (Figure 3.1). During November to January the days with catch (Dy^+) and the number of successful squares (Sq^+) depicted a similar trend, both within and outside the moratorium on FADs area (**Figure 3.1a and 3.2b**) while in contrast fishing time (*FT*) reminded high inside the protected area (**Figure 3.1c**).

Regarding sets on FADs (*FAD*), as expected, there was a decrease inside the area. Nevertheless this indicator increased outside, specifically around the moratorium zone (**Figure 3.2e**). Since recommendation [99-01] there were no further modifications and the measures established remained constant in the following years. It must be pointed out that when the voluntary moratorium on FADs was in force (until January 2000) the FADs sets were mainly made outside (**Figure 3.2e**). However when ICCAT recommendation [99-01] entered into force, the EU fleet carried out this fishing method both inside and outside the zone (**Figure 3.2f**) but not similar to previous levels. The catch of juveniles (< 1.8 kg) inside the moratorium on FADs area was similar to that outside (**Table 3.2, Figure 3.1h**). On the contrary, the number of sets on free-swimming schools (*FrSc*) remained concentrated inside (**Figure 3.2b, 3.2c**), reaching their peak in January; the same trend was logically observed for the catch of large yellowfin tuna on free schools (YFT^+) (**Figure 3.3f, 3.3h**).

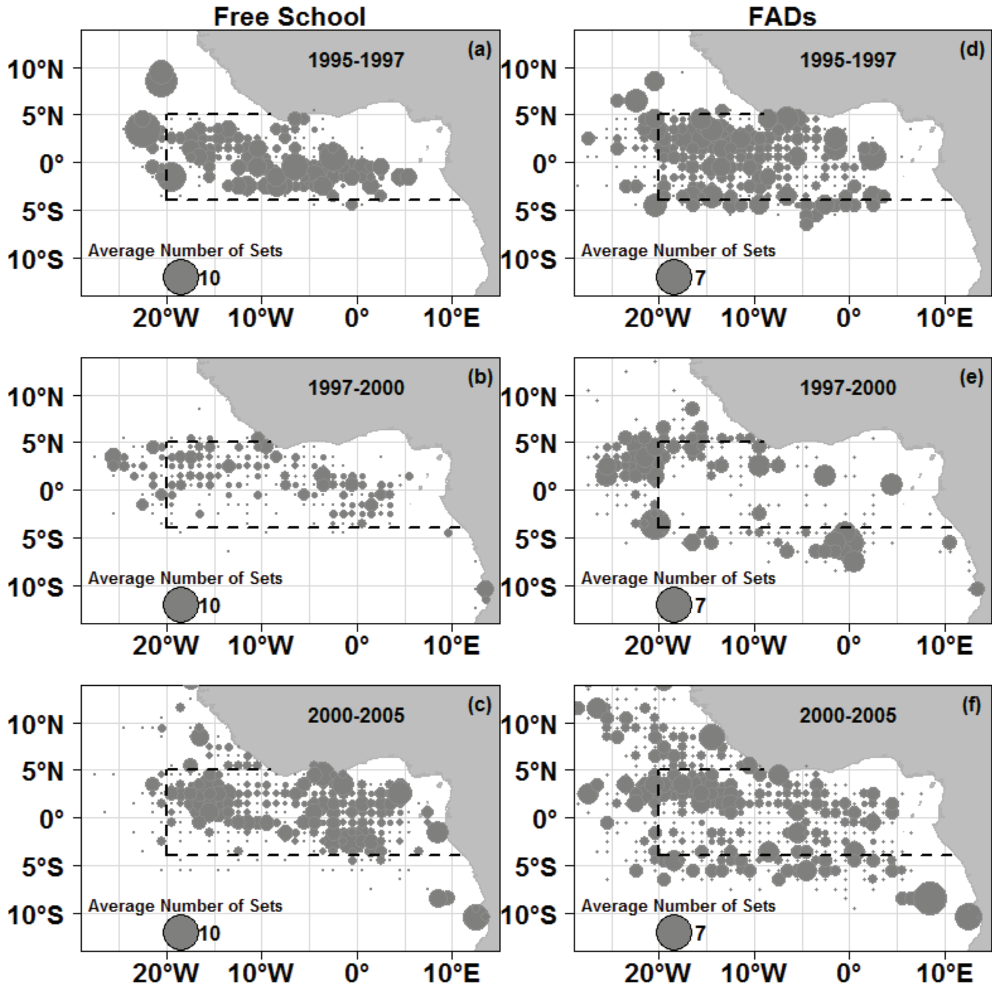

Figure 3.2 Spatial distribution (only for the three-month moratorium on FADs) of the average number of sets by vessel on free-swimming schools and FADs (by 1° x 1° square); corresponding to (a, d) before moratorium for the period 1995-1997, (b, e) the EU purse seiners voluntary moratorium on FADs 1997-2000, and (c, f) after the moratorium on FADs adopted by ICCAT (recommendation [99-01]), 2000-2005. Dashed black lines correspond to moratorium area.

3.1.3.1.2 Before-After approach on the moratorium on FADs area

From the BA analysis applied to inside the moratorium area, significant differences were evidenced in almost all the indicators, except the number of sets on free-swimming schools (*FrSc*) and the catches of large yellowfin tuna associated with this method (YFT^{+}) (**Table 3.2**). The days with catch (Dy^{+}), the number of successful squares (Sq^{+}) and the fishing time (*FT*) decreased once the moratorium on FADs entered into force (**Table 3.2**, **Figure 3.1**). Regarding the objective of the moratorium, there were significant differences in the number of sets on FADs (*FAD*) inside the area and therefore FADs catches (**Table 3.2**) as well as juveniles catch ($JuvC^{+}$) (**Figure 3.1**).

Regarding the outside region, only the number of sets on FADs (*FAD*) and the large yellowfin catch (YFT^{+}) differed significantly before and after the moratorium (**Table 3.2**). The first indicator increased while the second decreased (**Figure 3.1d, 3.1g**). Despite days with catch (Dy^{+}), successful squares visited (Sq^{+}) and fishing time (*FT*) decreased inside the moratorium area, no significant differences were observed outside (**Table 3.2**). On average the FADs catch ($FadC^{+}$) increased after the moratorium but not at a 5% significant level (**Table 3.2**).

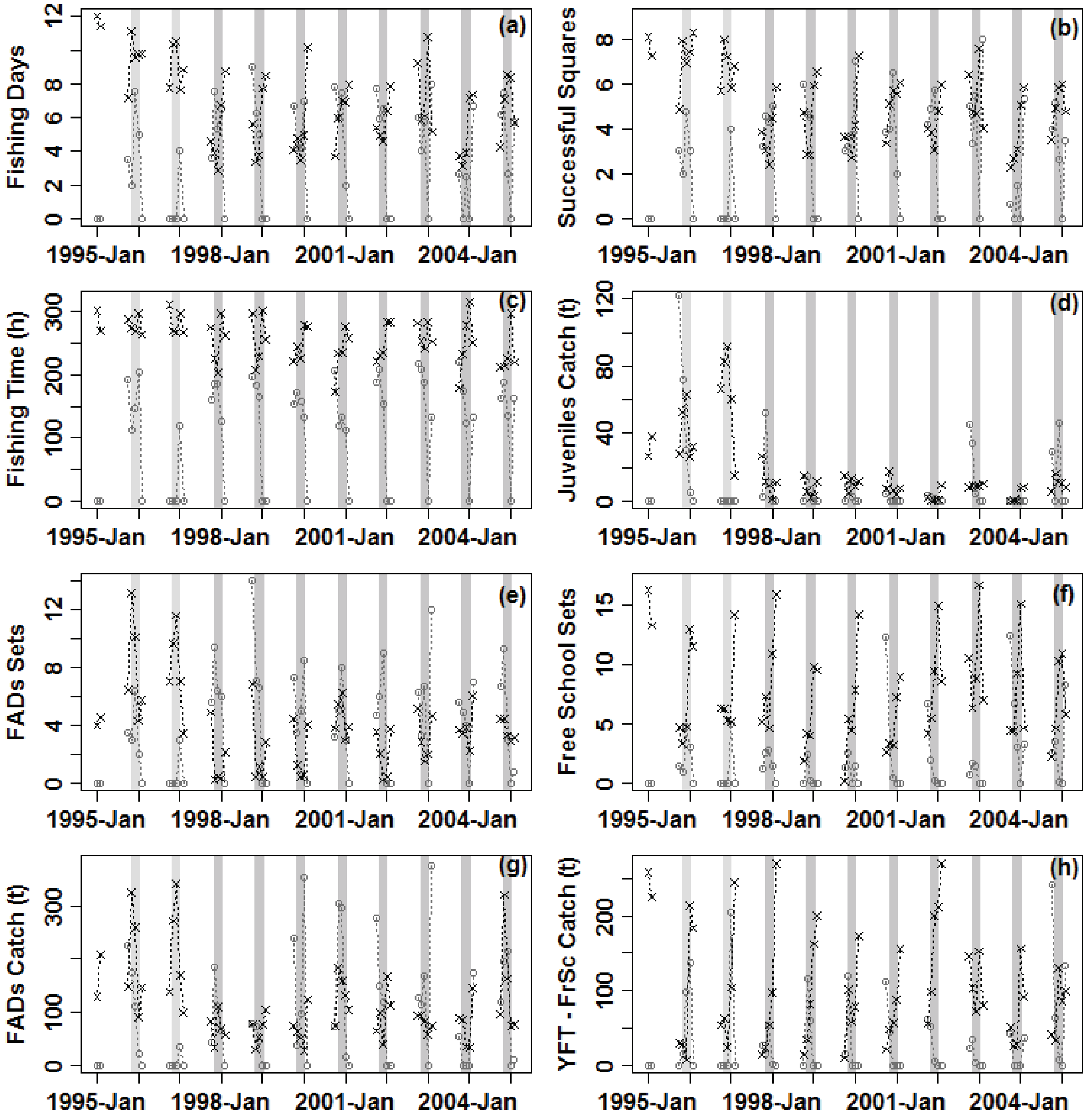

Figure 3.3 Fishery indicators inside (-x-) and outside (-o-) the regulated area during the three-month moratorium on FADs (± one month). Bars in light gray and bars in dark gray represent the restricted months before and when the moratorium on FADs was implemented, respectively.

3.1.3.2 No-take area closure

3.1.3.2.1 Fishing activities before and after ICCAT recommendation [04-01]

It was difficult to perceive the impact of such a small time-area closure (one month and a small area), and on the contrary the outside area was very large (**Figure 1.9**). Despite this size difference, before the no-take area was established some indicators behaved in average similarly both inside and outside (**Table 3.2**). The large yellowfin catch on free-swimming schools (YFT^+) and the FADs catch ($FadC^+$) (**Table 2, Figure 3.6g, 3.6h**) were both higher inside than outside the area, and this despite that the fleet spent more time outside than inside (**Table 3.2**). Except the month of regulation, the EU purse seine fleet had more activities outside the no-take area, but conversely during the month of regulation (November) there was an increase in the fishery indicators (**Figure 3.6**). Only the catch of large yellowfin tuna and the corresponding number of sets on free-swimming schools (YFT^+ and *FrSc*) did not present this general pattern (**Figure 3.6f, 3.6h**).

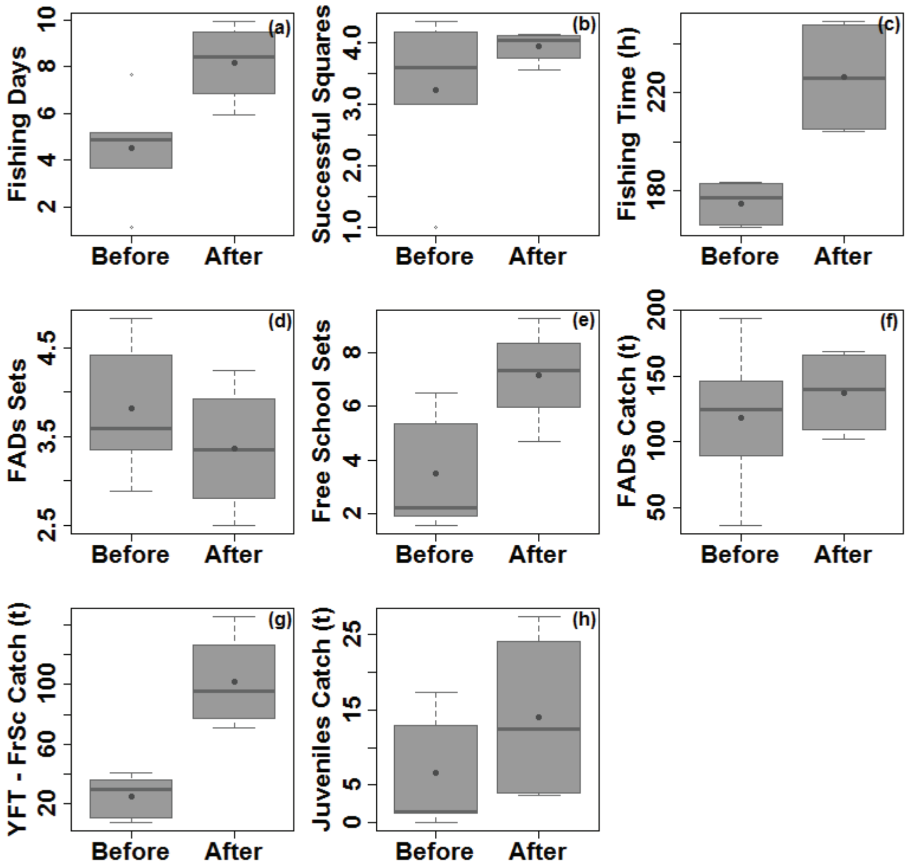

Figure 3.4 Fishery indicators box-plot outside the no-take Picolo area for the regulation month (November) before (2000-2004) and after (2005-2008) the moratorium on FADs. The average and the median are represented by points and stripes, respectively.

Table 3.2 Fishery indicators average Before-After each spatial regulation (moratorium on FADs and Picolo no-take area) and inside and outside each zone. Main statistics from Before-After analysis inside and outside of each spatial regulation (notice that fishing activities inside Picolo no-take area were banned). When the indicators were normal and homoskedastic an ANOVA was applied, otherwise Kruskall-Wallis rank sum test was applied.

Moratorium on FADs

		Inside		Outside	
Indicator	Description	Before	After	Before	After
Dy^{+}	Days with catch	10.16	5.77	4.65	5.08
Sq^{+}	Square visited with catches	7.34	4.36	3.45	4.12
FT	Fishing time (h)	282.3	251.8	145.9	160.72
FrSc	Number of free school sets	7.72	7.86	3.45	1.89
FAD	Number of FADs sets	8.57	2.05	3.6	6.05
$FadC^{+}$	FADs catch (t)	227.03	93.53	85.45	134.01
$JuvC^{+}$	Juveniles < 1.8 Kg catch (t)	57.81	6.67	26.8	9.75
YFT^{+}	YFT catch on Free school (t)	99.95	91.01	114.17	30.58

No-take area

	Inside	Outside	
Indicator	Before	Before	After
Dy^{+}	3.5	4.49	8.17
Sq^{+}	2.62	3.22	3.94
FT	124.78	174.8	226.53
FrSc	3.48	3.52	7.16
FAD	2.13	3.81	3.36
$JuvC^{+}$	3.63	6.59	14.01
YFT^{+}	60.01	24.52	102.01
$FadC^{+}$	142.8	118.1	137.67

Inside Moratorium on FADs

ANOVA					Kruskall-Wallis			
Indicator	Sum Sq	*df*	*F*	Pr(>*F*)	Indicator	X^2	*df*	*p-value*
Dy^{+}	104.4	1	29.071	8.54x10-6	*FT*	4.1272	1	0.0422
Sq^{+}	48.161	1	30.434	6.04x10-6	*FrSc*	0.0558	1	0.8133
$JuvC^{+}$		1	24.345	3.05x10-5	*FAD*	13.5804	1	0.00023
					$FadC^{+}$	9.4308	1	0.0021
					YFT^{+}	0.0558	1	0.8133

Outside Moratorium on FADs

ANOVA					Kruskall-Wallis			
Indicator	Sum Sq	*df*	*F*	Pr(>*F*)	Indicator	X^2	*df*	*p-value*
Dy^{+}	0.602	1	0.1321	0.7199	*FrSc*	2.6446	1	0.1039
Sq^{+}	1.498	1	0.542	0.4698	$JuvC^{+}$	1.1819	1	0.277
FT	725.3	1	0.6909	0.4152	YFT^{+}	4.8804	1	0.02716
FAD	19.799	1	4.4184	0.0478				
$FadC^{+}$	7793	1	0.7755	0.3885				

Outside No-Take Area

ANOVA				
Indicator	Sum Sq	*df*	*F*	Pr(>*F*)
Dy^{+}	30.014	1	6.6626	0.03641
Sq^{+}	1.1397	1	1.0603	0.3374
FT		1	12.141	0.01021
FrSc	29.344	1	6.7115	0.03591
FAD	0.4543	1	0.7691	0.4096
$JuvC^{+}$	122.24	1	1.2552	0.2995
YFT^{+}	13344.1	1	22.551	0.002087
$FadC^{+}$	850.9	1	0.3433	0.5763

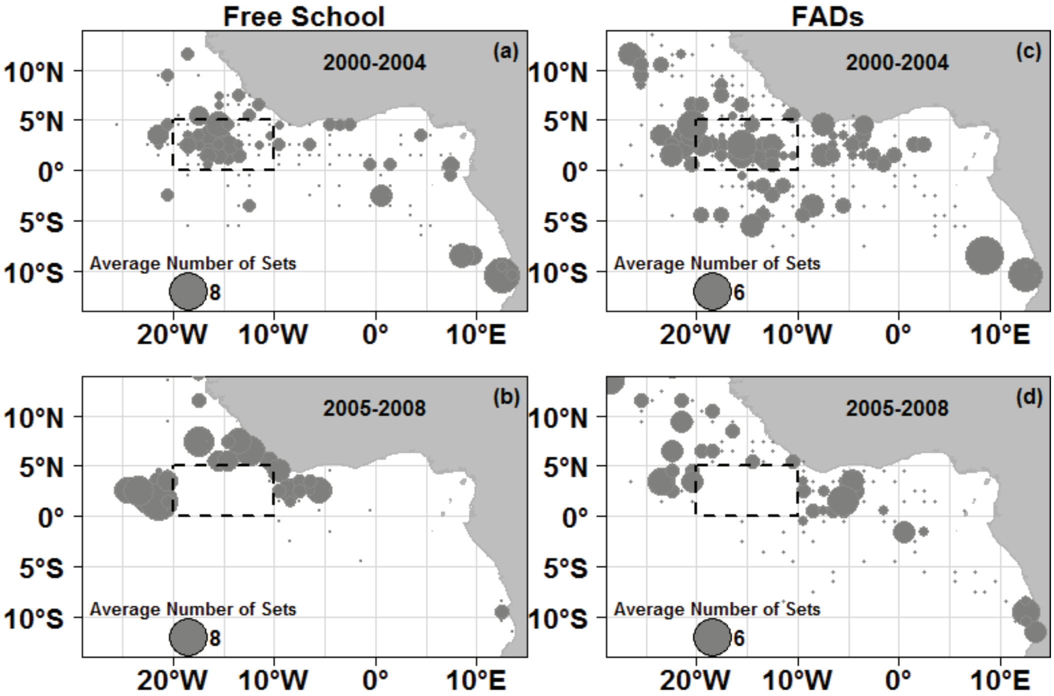

Figure 3.5 Spatial distribution during the no-take regulation month (November) of the average number of sets by vessel on free-swimming schools and FADs (by 1° x 1° square); corresponding to (a, c) before the implementation of the no-take area in 2000-2004, and (b, d) after the ICCAT recommendation [04-01] for the period from 2005 to 2008. Dashed black rectangle corresponds to the Picolo no-take area.

3.1.3.2.2 Before-After approach outside the no-take area

The fleet increased its efficiency (i.e., days with catch) and fishing time significantly, but there was no difference in the number of successful squares visited (**Table 3.2**). The number of days with catch (Dy^+) increased significantly after the implementation of the spatial no-take regulation while the effective area explored (Sq^+) remained unchanged (**Figure 3.4a and 3.4b**, respectively). Unlike the pattern observed during the moratorium on FADs, the number of sets on FADs (*FAD*) and the associated catch ($FadC^+$) did not increase (**Figure 3.4d, 3.4f, Table 3.2**).

In contrast to the slow increase in juveniles catch there was a significant increase in the number of sets on free schools (*FrSc*) and logically their associated catches (YFT^+) (**Figure 3.4h, 3.4e, 3.4g, Table 3.2**). After the implementation of the no-take area the number of sets on free schools (*FrSc*) was located all around the Picolo area (**Figure 3.5b**), while the sets on FADs (*FAD*) remained widespread throughout outside the regulated area (**Figure 3.5d**).

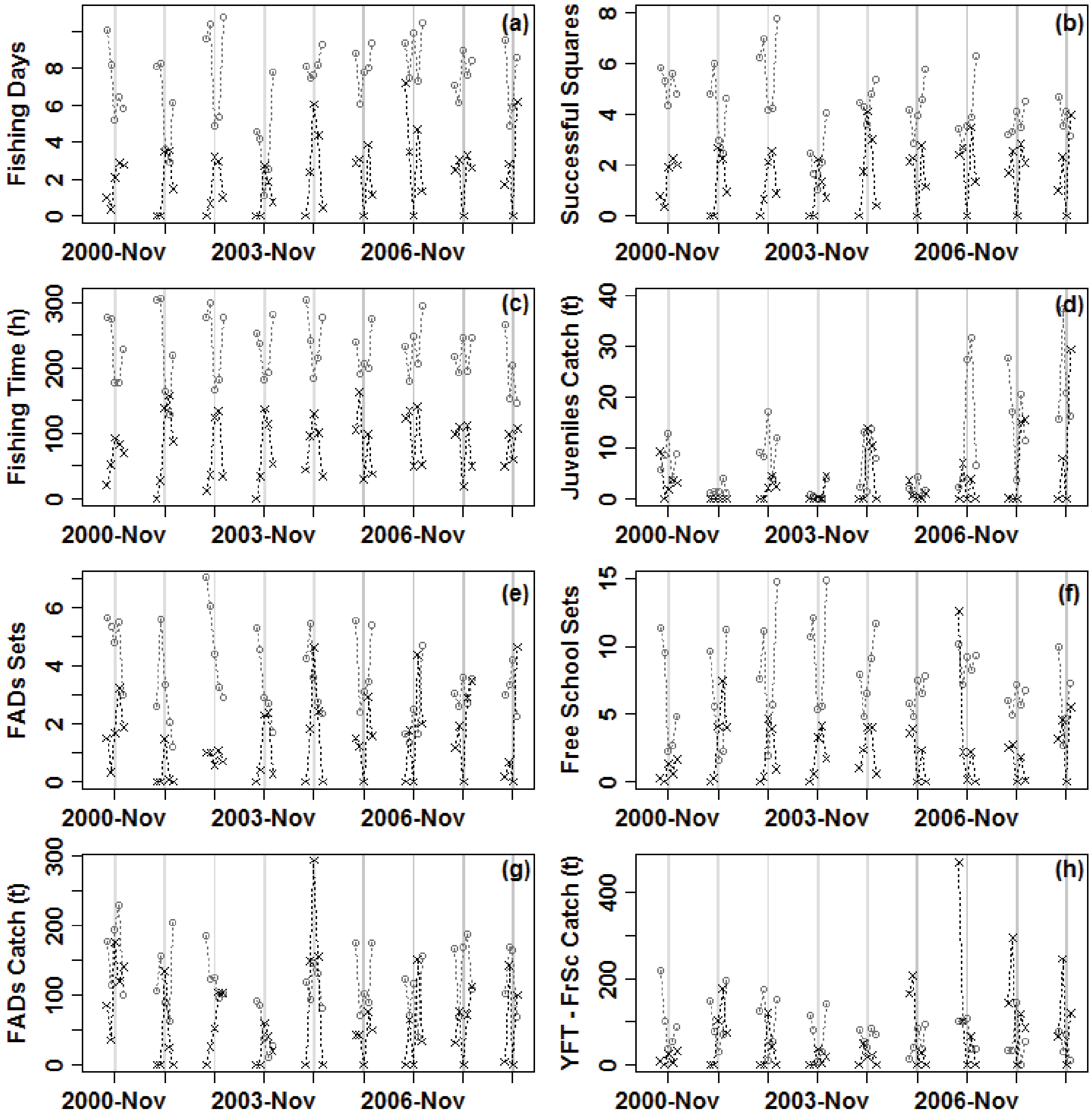

Figure 3.6 Fishery indicators inside (-x-) and outside (-o-) during the regulation month of November (± two months) when the Picolo no-take area was established. Bars in light gray represent November before closure and bars in dark gray indicate when the regulation was implemented.

3.1.4 Discussion

Marine protected areas (MPAs) could be considered as a powerful tool to face ever-increasing over-exploitation of marine resources and deterioration of ocean habitats (Agardy et al. 2011). According with Hastings and Botsford (2003), MPAs could have two fundamental objectives: preserve biodiversity and maximize fishery yields. The use of MPAs, however, could have shortcomings as reported by Agardy et al. (2011): (1) MPAs that as a result of their small size or poor design are ecologically insufficient; (2) inappropriate MPAs plan or management; (3) MPAs that fail due to the degradation of the unprotected adjacent areas; (4) MPAs that do more harm than good due to unexpected consequences of management; and (5) MPAs that seem to protect when in fact offer no such protection.

Furthermore MPAs should be selected on the basis of biological, oceanographic, physiographic, socio-cultural, political and economic criteria (Zacharias et al. 2006). Defining a time-area closure, in terms of no-take or prohibiting a specific fishing practice (e.g., FAD-fishing), is not trivial since the effectiveness of a spatial regulation for migratory fish depends on different factors such as: (1) the state of the stock; (2) some biological parameters (e.g., natural mortality of juveniles and exchange rates among fishing grounds); and (3) fishery characteristics (e.g., the fishery strategies developed due to the multispecies nature of the tropical purse seine fishery). In addition it has been shown that in presence of catch quotas, as recently adopted for bigeye, seasonal or permanent closure area may have the unwanted effect of increasing effort in adjacent areas open to fishing (Dinmore et al. 2003; Hilborn et al. 2004) and consequently such regulation should be implemented in conjunction with other control measures (Horwood et al. 1998; Murawsky et al. 2000; Stefansson and Rosenberg 2005; Kaiser 2005; Jaworsky et al. 2006; Little et al. 2010).

The location and size of MPAs are crucial issues which will determine the possible negative or positive effects from MPA enforcement, such as: (1) the reallocation of fishing effort outside the protected area; (2) MPA effectiveness facing oceanographic variability across space; (3) the time required for see the effects on stocks; and (4) the impact of overall higher total bycatch derived from the displacement of fishing effort to less productive areas (Zacharias et al 2006).

As mentioned previously, ICCAT was concerned in the mid-1990s about the increase in bigeye tuna and juveniles catch associated to FADs, as well as some indirect effects on potential changes in migration patterns and in health indicators (i.e., concept of ecological trap; Hallier and Gaertner 2008) or unexpected consequences on non-target associated pelagic species. In response to the ICCAT request about defining protected strata, the EU purse seiner associations established voluntarily the moratorium on the use of FADs. However, the possibility of also targeting non-associated large yellowfin allowed the fleet remaining inside the moratorium area. This is evidenced by viewing the lack of changes in some fishery indicators such as fishing time, number of sets and yellowfin catch made on free schools before and after the moratorium. One may expect a shift in fishing mode due to the compliance of the moratorium and consequently an increase in the number of sets on free schools, but such a situation did not occur (i.e., inside the area the indicator remained at the same level while outside there was a no significant decrease). The lack of increase in the related activities could be due to the fact that it was not worth fishing on free schools until January, when the season for large yellowfin starts (Goujon 2004a). The increase in FADs sets outside the moratorium area was a way to compensate for the losses in catch inside the area due to the ban on FADs fishing.

The absence of significant changes in the different indicators outside the moratorium area could be due to the fact that the EU fleet could continue to fish on free-swimming schools inside the area. Although a statistical comparison was not conducted directly between inside and outside the area for reasons explained in the Methods section, a barely significant increase in the number of FADs sets outside the protected area was showed (**Table 3.2**). This situation might be the consequence of a reallocation of the fishing effort rather than a change in fishing mode. Nevertheless, although this phenomenon has been described in fisheries regulated with a spatial moratorium (Poos and Rijnsdorp 2007; Powers and Abeare 2009), the fact that the related catches did not increase significantly, suggests that it was not possible to compensate for the losses inside the area.

In general, the moratorium on FADs was more respected when it was implemented on a voluntary basis (**Figure 3.2b**) than it was formally established by ICCAT for all fleets. It must be stressed that the non-compliance of the FADs moratorium by some purse seiners operating under the flag of Ghana hindered the evaluation of this type of spatial regulation, limiting the conclusions of management studies conducted by ICCAT (ICCAT 2009) and may have stunted the compliance of the FADs regulation by the EU purse seiners as suggest the increasing cases of non-respect during the second period. Ariz et al. (2009) reported that landings of skipjack and juveniles of bigeye tuna inside the moratorium area increased during 2000-2003 with respect to the period 1997-1999. These species are caught mainly on FADs and concern small sized tunas (Fonteneau et al. 2000a). Here, despite the EU purse seine fleet continued to fish on FADs, the catches on juveniles remained low in comparison to the catches before the moratorium. A possible explanation could be the skippers' ability to distinguish and avoid tuna schools that have only juveniles (Goujon 2004b).

Because of the IUU fishing activities, ICCAT modified the moratorium and a new time-area closure (termed Picolo area) entered into force in 2005. The Picolo area was selected because it is known to support large concentrations of juvenile tunas likely due to oceanographic-specific conditions (Evans et al. 1981; Prince et al. 2010) and to the abundance of one of the favorite mesopelagic preys of tuna juveniles, *Vinciguerria nimbaria* (Ménard et al. 2000).

Compared to the moratorium on FADs stratum, however, there was a large reduction in terms of space (by almost 25% of the surface of the previous regulation) and time (only November, i.e., 33% of the 3-month period of the moratorium). Another major change was the fact that the new spatial regulation referred to the restriction of all types of surface fishing activities. Cass-Calay et al. (2006) and Brooks and Mosqueira (2006) indicated that the new closed area would not be effective to reduce the catches of all tuna species landed in the total Atlantic. The results here confirm these predictions. Effectively, the inside no-take area was respected, and there were some increases in the indicators outside the area. This may be due to the fact that it was possible to fish in a stratum that was known to have a high density of tropical tunas and fishing activities on FADs. Hence, there were no restrictions to fish with this method in the rest of the Gulf of Guinea and, as a result, the catches associated with this method were not expected to undergo any change. In general, it was difficult to evaluate the effects of this stratum since it was too small in surface and too short in time. Furthermore, within the framework of a BACI analysis, the results of the no-take area must be used with caution because the period that was considered as "before" regulation measure had already supported some restrictions on fishing activities (the Picolo area is included in the moratorium region on FADs and consequently is not independent). The inefficiency of the no-take area led ICCAT to reconsider the effectiveness of such a time-area closure to protect juvenile tunas. Some changes in surface area, time-area closure and in restriction on FADs activities were considered (recommendation [08-01]). These changes would be a return to the moratorium established in 1997.

The use and effectiveness of area closures as a management tool have been estimated with respect to changes in community structure (Fisher and Frank 2002; Dinmore et al. 2003; Hiddink et al. 2006; Jaworski et al. 2006), abundance species (Greenstreet et al. 2006; Lincoln-Smith et al. 2006; Smith et al. 2008; Jensen et al. 2010), yield resource (Holland and Brazee 1996; Holland 2003; Hart 2006), economic profits (Smith and Wilen 2003; Sanchirico et al. 2006; Armsworth et al. 2010). However, there are few studies that consider the fishermen component (Wilen et al.

2002; Murawski et al. 2005; Kellner et al. 2007; Powers and Abeare 2009). Some authors (Johannes et al. 2000; Wilen et al. 2002; Salas and Gaertner 2004, Kaiser 2005; Branch et al. 2006, Poos and Rinsdorp 2007) noted the importance of taking into account fishermen's responses to management measures, basically because fishermen adapt their fishing practices to continue to catch the fish. Together with this, the effects on fishing effort (in terms of target species) and its spatial re-allocation as a response of fleet are logically evaluated. While in this study the nominal fishing effort showed almost no changes as a result of regulatory measures, when the analysis was conducted by fishing mode (in number of specific sets), it was possible to better understand the fishermen's responses to spatial regulations.

This study is an example of how different time-space management regulations (the moratorium on FADs and the no-take area) could have positive and negative effects on the fleet behavior and therefore on the target species. Even if our objective was not to evaluate the effects of the voluntary basis moratorium (1997-2000), it seems to have had better results in protecting the resource. On the other hand, we have not estimated the effects of both the moratorium on FADs and the no-take area to the months of the year free of regulation measures. However, Ariz et al. (2009) reported a decrease in the annual total landings of the three principal species caught by the Spanish purse seine fleet since the moratorium on FADs. This led to some changes in FAD-fishing tactics in the French purse seine fleet, as showed in Chapter 2, passing from 2 tactics before the moratorium on FADs to 4 tactics after. The important issue of how to manage the multispecies feature of the tropical purse seine fishery was also partially analyzed by Harley and Suter (2007). They estimated the potential to reduce purse seine bigeye catch considering no reduction in skipjack catch of a time-area closures on FADs in the eastern Pacific Ocean, finding that even with a decrease in bigeye catches it would be insufficient for sustainability.

Finally, as a complement to ecological information and population dynamic models, modeling the fleet dynamics is required to anticipate the fishermen's responses to different scenarios in regard to different spatial regulation measures, as well as to evaluate the effects of combining other management regulations with time-area closure.

3.2 Effects of season-length restriction in the Mexican tropical tuna purse seine fleet in the eastern Pacific Ocean.

3.2.1 Introduction

Another management tool often used to reduce fishing effort besides time-area closures is season-length restriction. Whether this adjustment is possible or not depends on characteristics of the species' life history (seasonal recruitment patterns, growth rates, and natural mortality rates) and on the effects of seasonal closure on the pattern of fishing effort (Watson et al. 1993). However, closed seasons do not usually reduce fishing effort, because fleets may increase their fishing efficiency and capacity to maintain catch levels (Branch et al. 2006; Fulton et al. 2011).

Similarly to the eastern tropical Atlantic tuna purse seine fishery, in the eastern Pacific Ocean (EPO) fishery has been subject of several regulatory measures. As mentioned in Chapter 1 a season-length restriction was implemented in 2002 in this region. Some adjustments were made on it, but the period closed remained the same (i.e. December). Different studies have evaluated management regulations in the EPO, mainly on the stock assessment (Maunder 2002; Maunder and Harley 2006; Zhu et al. 2012) and on multiple management objectives (Enríquez-Andrade and Vaca-Rodríguez 2004; Vaca-Rodríguez and Enríquez-Andrade 2006). However, as seen for the eastern Atlantic tuna fishery, there is no study that has evaluated the fishermen adaptive responses to the establishment of the closed seasons. As mentioned earlier in this chapter, it is necessary to account for the fleet response to time-area regulation to improve the fishery management. In this sense, tuna purse seine fleet dynamics has been studied in the EPO but in terms of general fishing strategies without considering fishery regulations (Vaca-Rodríguez and Dreyfus-León 2000; Dreyfus-León and Vaca-Rodríguez 2003; Solana-Sansores et al. 2009) and individual behavior-based model (Dreyfus-León and Kleiber 2001). For this reason, in this section we focused on the evaluation of the adaptive responses of the Mexican purse seine fleet derived from the implementation of season-length restriction, using some fishery indicators.

3.2.2 Material and Methods

3.2.2.1 Data

Observer program data from Mexican tuna purse seiners operating in the EPO have been collected by the *Programa Nacional de Aprovechamiento del Atún y de Protección de Delfines* (PNAAPD) since 1992. The PNAAPD was established within the framework of the research fund FIDEMAR. This fund is formed by the National Chamber of the Fishing Industry (CANAINPESCA), the Federal Government (CONAPESCA-INAPESCA), and the Mexican foundation for the preservation of marine wildlife (FUMDAMAR). The data used in this section are from three sources: (1) the observer program carried out by the PNAAPD, corresponding to 50% coverage of Mexican fishing trips, (2) departure and return dates of each fishing trip and (3) monthly time series of climate indices from NOAA, for instance, Niño3 area (5°N-5°S, 150°W-90°W).

3.2.2.2 Fishery indicators

For the period 1992-2001 (prior to the implementation of closed seasons), the catch limit was reached only in 1999 and consequently the fishery was closed in November 23. Because of Mexican purse seiners are the main fishing fleet on dolphin-associated tuna fishing while the others nations fish mainly on FADs, it is assumed that during the period 1992-2001 fishermen were not encouraged to exacerbate fishing pressure. This means that fishing competition is mainly among Mexican vessels. However, the implementation of the closed seasons is an incentive to be more efficient because the year to year tuna abundance is affected by climate variability (e.g. ENSO). For these reasons it was decided to estimate the numbers of days in port, considering that this indicator is easily controlled by fishermen, hastening fish landing and/or loading rapidly the supplies to the next trip. Days in port (*P*) were estimated with departure and return dates in a quarterly basis for two periods, prior (1992-2001) and after (2002-2008) the implementation of season-length restriction.

Then to evaluate whether there was an additional effect on the main fishing strategies, i.e., dolphin-associated tuna and free-swimming school (*FS*), the numbers of sets (*MAM*, *FS*, respectively) and the corresponding catches (*MAMc*, *FSc*) were estimated by fishing modes in a monthly basis and by vessel size (<1000 t, ≥1000 t) associated to each fishing mode from observer data.

3.2.2.3 Statistical analyses

3.2.2.3.1 Days in port

Due to the characteristic of this indicator, a Wilcoxon-Mann-Whitney test was used to evaluate if there were differences in the number of days in port before and after the season-length restriction. The comparisons were conducted between pairs of quarters (i.e., quarter 1 before and after and so on). The null hypothesis of the test is that the two populations have the same response distribution against the alternative that they are different. The test is used to detect "shifted alternatives", i.e., the two population distributions have the same general shape (including dispersions), but one of them is shifted relative to the other by a constant amount under the alternative hypothesis.

3.2.2.3.2 Effects on the fishing modes

To assert the season-length restriction effects on the fishing modes, we need to account for the noisy climate impact on the resource (as mentioned, the interannual variability of climate in the EPO is more pronounced than in the tropical Atlantic Ocean). Thus, any change in fishery indicators would be due to this variability and not by the season-length restriction. Moreover, vessel size is important because in general, large vessels use to fish on dolphin-associated tuna schools offshore, targeting mainly large yellowfin, while small vessels use to fish near to coast on free-swimming schools. Thus, the season-length restriction may affect more one vessel size than the other.

Therefore, this analysis was carried out with a generalized linear model (GLM) which includes:

the Before-After component which is the interest of the analysis, the vessel size was included because large vessels mainly fish on dolphin-associated tunas schools, while small vessels fish mainly on free-swimming school, and a covariate to take into account the climate variability (*cv*), with the Niño1+2, Niño3 areas temperatures or the Southern Oscillation Index (SOI). The model design is expressed as follows:

$$Y = \beta_0 + cv \times \beta_1 + BA \times \beta_2 + VS \times \beta_3 + BA \times VS \times \beta_4$$

where *Y* is the indicator (*MAM, FS, MAMc* or *FSc*) , the period (*BA*), defined as 1992-2001 vs. 2002-2008, the vessel size (*VS*), with two categories (<1000 t and ≥1000 t), the climate variability (*cv*), with the Niño1+2, Niño3 areas temperatures or the Southern Oscillation Index (SOI), the last term is the interaction between the period and the vessel size. Because of the nature of the *MAM* and *FS* indicators (i.e., they are counts) it was used a Poisson GLM (link function=log), in which was detected overdispersion, thus the standard errors were corrected using a quasi-GLM where the variance is given by ϕ x μ where μ is the mean and ϕ the dispersion parameter. In the case of the catches indicators (*MAMc* and *FSc*) it was used a Gamma GLM (link function=inverse).

3.2.3 Results

3.2.3.1 Adaptive response to season-length restriction

Table 3.3 Mean and median of days in port before (1992-2001) and after (2002-2008) the implementation of the season-length restriction by quarter. Main statistics from Before-After analysis.

Quarter	Z	p-value	Mean		Median	
			Before	After	Before	After
Q1	11.3794	$< 2.2 \times 10^{-16}$	27.18	12.21	17	9
Q2	3.6709	2×10^{-4}	20.66	15.88	15	12
Q3	4.3969	1.10×10^{-5}	24.88	18.16	16	13
Q4	5.3516	8.72×10^{-8}	25.49	14.85	14	9

As evidenced in **Table 3.3**, before the implementation of the closed seasons purse seiners spent more time in port than from 2002 onwards. In average the number of days in port decreases from 24 days before the establishment of the closed season to 15 days after. The first and fourth quarters of the year showed the major differences in the number of days in port before and after the closed season implementation (**Figure 3.7**).

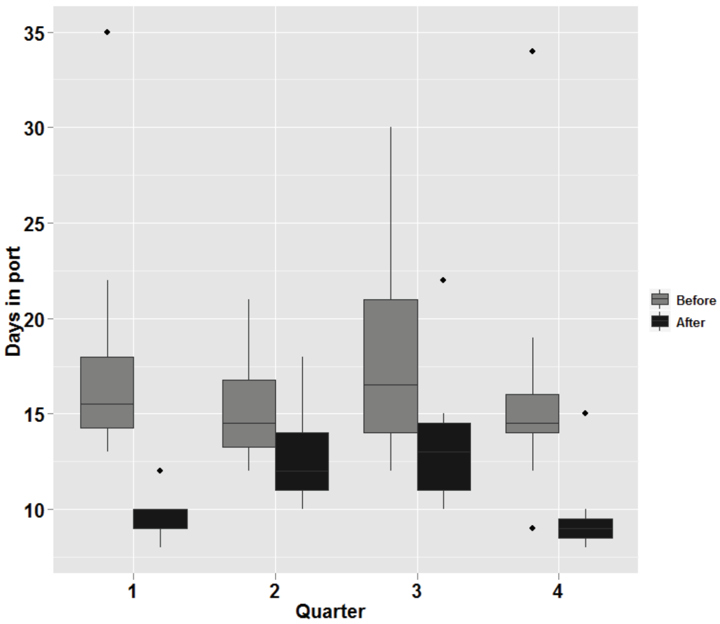

Figure 3.7 Quarterly number of days in port by the Mexican purse seine fleet before (grey boxes) and after (black boxes) the implementation of closed seasons in the EPO.

3.2.3.2 Effects on the fishing modes and associated catches

Table 3.4 Average catch and number of sets on dolphin-associated school and free-swimming school before (1992-2001) and after (2002-2008) the season-length restriction and by vessel size (upper part), and average values of the interaction of these terms (bottom part).

	Dolphin-associated school				**Free-swimming school**			
	Before	*After*	*<1000 t*	*≥1000 t*	*Before*	*After*	*<1000 t*	*≥1000 t*
Catch	1611.4	1637.5	449.1	2794.6	816.4	587.5	596.4	854.1
Sets	85.0	101.1	37.1	145.8	52.0	37.0	48.9	43.2

	<1000 t		*≥1000 t*		*<1000 t*		*≥1000 t*	
	Before	*After*	*Before*	*After*	*Before*	*After*	*Before*	*After*
Catch	501.0	370.5	2721.9	2904.5	695.4	446.7	937.4	728.2
Sets	39.4	33.6	130.6	168.7	58.4	34.4	45.6	39.5

For dolphin-associated tuna schools, the results from the ANOVA showed that the catch (*MAMc*) associated with this fishing mode had no significant differences before-after (*BA*) the season-length restriction (**Table 3.5, Figure 3.8-top left**), even if the number of sets (*MAM*) increased after the regulatory measure. The rest of the results from the variance partition among factors and the interaction evidenced the importance of taking into account for vessel size to assess accurately the impact of the time regulation on catches and number of sets by fishing modes. The Niño3 area SST was more related with both indicators than the SOI and Niño1+2 indices. The *a posteriori* test (Annex B1) from the interaction between vessel size and before-after showed that the increase in number of sets was significant only for large vessels.

Table 3.5 ANOVA of the different GLM used to evaluate the effects of the implementation of the season-length restriction on the fishery indicators.

Dolphin-associated schools sets (*MAM*)

	df	Deviance	Resid. *df*	Resid. Dev	Pr(>*Chi*)
NULL			391	25228	
Niño3	1	514.3	390	24714	0.00001
VS	1	13470.7	389	11243	<2x10^{-16}
BA	1	278.9	388	10964	0.001
VSxBA	1	247.7	387	10717	0.003

Dolphin-associated schools catch (*MAMc*)

	df	Deviance	Resid. *df*	Resid. Dev	*F*	Pr(>*F*)
NULL			391	775.6		
Niño3	1	9.791	390	765.81	17.0278	0.00005
VS	1	286.05	389	479.76	497.4518	<2x10^{-16}
BA	1	0.08	388	479.68	0.1388	0.710
VSxBA	1	4.461	387	475.22	7.7584	0.006

Free-swimming schools sets (*FS*)

	df	Deviance	Resid. *df*	Resid. Dev	Pr(>*Chi*)
NULL			391	14989	
Niño1+2	1	184.61	390	14804	0.037
VS	1	69.92	389	14734	0.198
BA	1	429.71	388	14304	0.001
*VS*x*BA*	1	147.58	387	14157	0.062

Free-swimming schools catch (*FSc*)

	df	Deviance	Resid. *df*	Resid. Dev	*F*	Pr(>*F*)
NULL			391	856.47		
SOI	1	3.2292	390	853.24	3.1245	0.078
VS	1	12.6401	389	840.6	12.2304	0.0005
BA	1	10.215	388	830.39	9.8839	0.0018
*VS*x*BA*	1	2.135	387	828.25	2.0658	0.151

Contrary to the dolphin-associated school indicator patterns, the number of sets on free-swimming schools was not affected by the vessel size, but it was by the before-after season-length restriction. This resulted in a decrease in number of sets and because the interaction term was almost significant (*p*-value = 0.062), *a posteriori* test (Annex B1) was carried out, showing that this decrease was only in small vessels (**Figure 3.8-bottom left**). For this indicator (*FS*) the climate index related was the SST in the Niño1+2 area. Regarding the catch associated to free-swimming schools, the term vessel size (*VS*) showed that large vessels caught more than small ones (**Table 3.4**). The term before-after (*BA*) resulted in a decreased in the catch associated to free-swimming schools from 817 t to 587 t per month (**Table 3.4**). However, the interaction *VS*x*BA* was not significant (**Table 3.5, Figure 3.8-bottom right**).

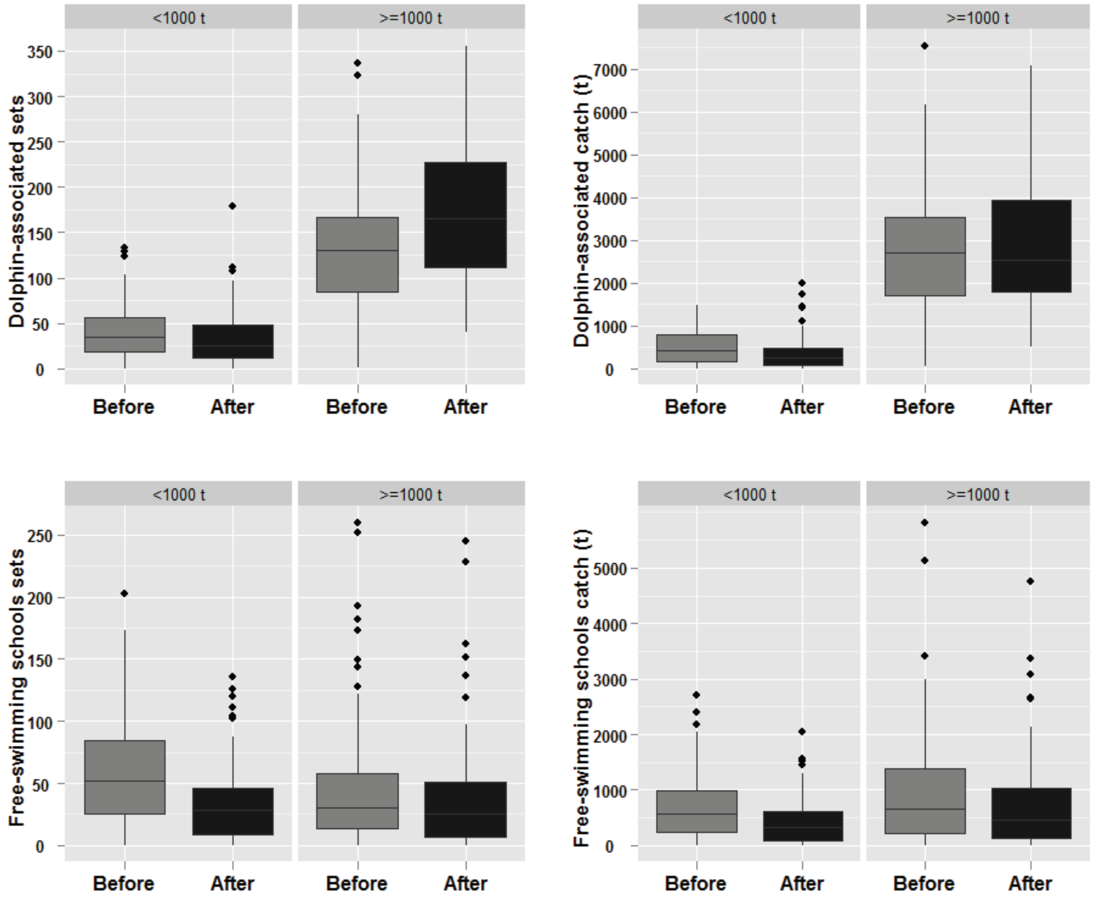

Figure 3.8 Number of sets on dolphin-associated schools (top left panel) and free-swimming school (bottom left panel) and corresponding catches (top right panel and bottom right panel). The boxplots are partitioned by vessel size (<1000 t, ≥1000 t), and Before-After closed seasons implementation.

3.2.4 Discussion

Seasonal regulation is commonly used as a management tool, and reducing the length of the fishing season is a way to limit catch by controlling fishing effort. However, season-length restriction does not usually reduce effort as much as anticipated (Fulton et al. 2011). Besides the different sources of uncertainty in fisheries, when management measures are implemented, fishermen adapt their activities to increase, or at least maintain their income (Salas and Gaertner 2004).

The implementation of season-length restriction in the EPO was an interesting case to analyze how the Mexican purse seiner fleet adapted to this management measure. According to our findings, the adaptive response was to decrease the time spent in port (*P*) and consequently to spend more days at sea. However, the season-length restriction affected mainly the dolphin-associated tuna fishing, which is the main fishing mode of the Mexican fleet. It was showed that besides the reduction in number of days in port, the increase in number of sets resulted in maintaining the previous catch levels. In the case of free-swimming school the season-length restriction resulted in a decrease in sets and associated catch, affecting both vessel size categories.

This result has an important consequence because, as mentioned earlier, in the EPO large vessels (≥1000 t) use to fish offshore, targeting mainly large yellowfin on dolphins, while in general small purse seiners fish near to the coast, on free-swimming schools.

Because of the continuous increase in purse seine capacity despite the regulation measures, IATTC implemented recently in 2011 the resolution [C-11-01] which established two closed seasons of two months each. Closed seasons can, however, be a useful management tool if reproductive outputs of individuals are negatively affected by fishing activity (Arendse et al. 2007). In the EPO, yellowfin spawning occurred continuously throughout the year between 0° and 20°N latitude, with no pronounced seasonal patterns in intensity (Knudsen 1977, Schaefer 1998). This means that the season-length restriction has mainly been established to control fishing effort, not directly for protecting spawners or juveniles (as tentatively done in the eastern Atlantic), only to avoid reduction on the resource production. However, as it was mentioned in the analysis of the EU purse seine fleet, it is important to take into account for fishermen behavior as the restriction affected differently the different components of the purse seine fleet.

In the World Ocean, tuna fisheries are multispecies, multigear and concern different countries with different socio-economic objectives. This explains why tuna RFMO have difficulty to reach consensus in terms of regulation measures. In the EPO, the yellowfin tuna fishery, longliners are mainly from Japan, Republic of Korea and Taiwan and most of the purse seiners are from other nations. Most of the dolphin-associated schools sets are made by Mexican and Venezuelan fleets, and most of the FADs sets are made by Ecuadorian vessels. Therefore, any allocation of effort among these methods would require agreement among the states concerned (Maunder 2002).

For all of these reasons, it must be kept in mind that season-length restrictions do not only affect dolphin-associated schools fishing but all tropical tuna fisheries (i.e., longline, pole-and-line and purse seine fisheries). However, it is difficult for a management agency to reallocate the total effort among the different fleets. This may be perceived to favor one group over another, even if there are good reasons for the allocation (Maunder 2002).

Summarizing, this section showed adaptive responses of the Mexican purse seine fleet facing the season-length restriction to at least maintain the catch levels observed before 2002. Reducing the time spent in port allowed fishermen operate more time at sea than before the regulatory measure. However, these results must be taken with caution, because 1) the analysis should be consider the other fleets operating in the EPO, especially those involved in FAD-fishing, and 2) due to climate variability the results obtained here could be affected by extreme oceanographic event, even if in the analysis of covariance the indices (e.g. Niño3 area) were included and found statistically significant.

ANNEX B1

Table B1 Tukey multiple comparisons of means applied on the fishery indicators of the Mexican purse seine fleet. The comparisons of interest were small vessels (<1000 t) before and after, and large vessels (≥1000 t) before and after the season-length restriction.

Indicator	Level	Estimate	Std. Error	*z*	Pr(>|*z*|)
Dolphin-associated schools catch (MAMc)	Before-<1000 t - After-<1000 t	-7.03×10^{-4}	3.75×10^{-4}	-1.875	0.0607
	Before-≥1000 t - After-≥1000 t	3.12×10^{-5}	2.61×10^{-5}	1.193	0.2328
Dolphin-associated schools sets (MAM)	Before-<1000 t - After-<1000 t	0.16072	0.12516	1.284	0.199
	Before-≥1000 t - After-≥1000 t	-0.26224	0.0645	-4.066	4.78×10^{-5}
Free-swimming schools sets (FS)	Before-<1000 t - After-<1000 t	0.5154	0.126	4.09	4×10^{-5}
	Before-≥1000 t - After-≥1000 t	0.1266	0.1659	0.763	0.4452

Chapter 4

Consequences of changes in technology and fishing strategies on non commercial tunas and on associated fauna

4.1 Introduction

In addition to the long-term sustainability of the fishing stocks, managing and mitigating bycatch (i.e. the incidental catches of undersized classes of the target species and other non-target species) is nowadays the most pressing issue facing the commercial fishing industry worldwide. Bycatch is also a major concern to conservation bodies (both governmental and nongovernmental) and the wider public (Alverson et al. 1994; Hall and Mainprize 2005). Bycatch ranges from very rare events to very large mortalities, from serious conservation threats to negligible impacts on populations (Hall 1996). This practice is considered to be responsible for economic loss and ecological effects on keystone species which are important to the performance and structure of ecosystems (Alverson et al. 1994; Garcia et al. 2003).

Vulnerable species groups subject to bycatch include many taxa such as seabirds, sea turtles, marine mammals, elasmobranchs and other bony fishes species. Many of these species are particularly vulnerable to overexploitation of older age classes and can decline over short temporal scales (decades and shorter). Due to their K-selected life-history strategy, characterized by long life spans, slow growth, delayed sexual maturity, low fecundity, and low natural mortality rates of older individuals, they are assumed to recover slowly from large declines (Hall et al. 2000; Lewison et al. 2004).

The immediate consequence of bycatch is population declines, thus it is important to indentify demographic effects driven by a given fishery. However, evaluating the bycatch impact on the epipelagic ecosystem may be difficult, because pelagic populations are fundamentally difficult to monitor. Even for species with a terrestrial component to their life cycle (e.g. sea turtles and seabirds that nest on land), it is hard to detect significant changes in the total population (Lewison et al. 2004). However, given the demographic vulnerability of long-lived species, even a high fishing selectivity, capturing incidentally only few individuals, can have serious population-level effects.

Fisher behavior and fleet dynamics are directly involved in the level of bycatch resulting from a wide range of fishermen's strategies. For instance, fishing effort is generally allocated to areas or seasons where target species are gathered and may be associated with non-target species (e.g. fishing on FADs). It should be noted that the incidental species caught may be discarded (species with no economic value or due to regulatory measures) or retained on board as a by-product (non-target species with high market value) and landed in local markets (Hall 1996; Romagny et al, 2000). Another effect resulting from fishing practices is the setting on tuna schools associated with whales and whale sharks. Purse seining on these species not hauled on board may result in incidental mortality on whales and whale sharks.

On average, quantitatively the overall ratio of bycatch to total catch estimated in the tropical tuna purse seine fisheries (7.5%) remains low since it has an almost ten-fold lower ratio than shrimp fisheries and a six-fold lower ratio than tuna longline fisheries (Kelleher 2005). However, qualitatively the bycatch generated from FAD-fishing might become a problem to purse seine fisheries management, mainly for conservation of vulnerable species. FAD-fishing occasionally capture sea turtles (Hall 1998, Amandè et al. 2010), billfishes (specifically marlins, although bycatch is low; Gaertner et al. 2002), and in the case of sharks, two species predominate: the silky shark (*Carcharhinus falciformis*), comprising up to 90% of the shark catch, and the oceanic white tip (*C. longimanus*) (Hall et al. 2000; Molony 2005; Amandè et al. 2008).

It must be stressed that FAD-fishing bycatch is considerably greater (15 t/100 t of tuna landed) than bycatch taken by purse seining on free-swimming schools (2.8 t/100 t of tuna landed) of total catch (Bromhead et al. 2000; Amandè et al. 2010). In the western Indian Ocean, bycatch are also larger in FADs sets than in free-swimming school sets (93% and 45% of the occurrences, respectively; Romanov 2002, Amandè et al. 2008).

Along this dissertation manuscript, it has been stood up the effects of FAD-fishing mainly related to commercial tuna. Notwithstanding, the aim of this chapter is to focus on the effects of the EU (France and Spain) tuna purse seine fleet fishing strategies (free-swimming school fishing and FAD-fishing), the underlying effects of new fishing devices, and the potential changes in fishing grounds on the bycatch by species groups associated with tuna catches. Based on data from observer programs conducted on two different periods of time assumed to characterize (i) the period of full development of FAD-fishing (unfortunately there is no significant observer data available in the early nineties) and (ii) the recent years, we analyzed 1) changes over time in variability of the bycatch species composition by fishing mode (bycatch species composition by temporal strata evidenced from Chapter 2, is also described), 2) the species richness of the bycatch by fishing modes is estimated as well as estimates of the number of bycatch species that can potentially be caught. We complemented the analysis by 3) showing the spatial distribution of bycatch species listed in the Red List of Threatened Species of the International Union for Conservation of Nature (IUCN), and finally 4) a descriptive analysis of sets made on whales and whale sharks (i.e., two important species for the epipelagic ecosystem but not considered as bycatch since in general they are used as sighting indices associated with tuna schools but are not hauled onboard).

4.2 Material and Methods

4.2.1 Data

Bycatch data were collected during two observer programs carried out by France and Spain in the eastern Atlantic Ocean. The first program (i.e., the EU Research Bigeye Program; Ariz and Gaertner 1999) was conducted from mid-1997 to mid-1999. Data were collected by observers through 51 fishing trips with an overall fishing trips coverage rate of 8.7%. From a total of 1238 sets, 787 sets were made on free-swimming schools and 451 on FADs (as defined in Chapter 2). Data from the second program (i.e., Data Collection Framework: DCF) corresponded to the period 2005-2008. Along 35 fishing trips (coverage rate at about 3.8%) 754 sets were observed (409 sets on free-swimming schools and 345 on FADs).

Owing to time constraints during the set (and bearing in mind that the first observer program was devoted to bigeye tuna) some additional bycatch tasks were difficult to accomplish for observers on board. Consequently, in some circumstances some species may have not been correctly identified or classified in higher taxa. Moreover, observers reported either numbers of individuals or weight by species (whenever the number of individuals was too high). For all of these reasons and according to the objectives of the study the analysis was carried out 1) through groups of species (i.e., minor tunas, billfishes, sharks, rays, turtles and other bony fishes), and 2) using presence/absence instead of counts.

Data of sets on whales and shark whales were obtained from logbook data from 1981 to 2008. Skippers often specify the type of association when setting a tuna school. It was possible to obtain coordinates of sets made on both type of associations, but there is no information about hurting or mortality caused by setting on these species.

4.2.2 Analysis of the effects of the fishing strategies on the bycatch species composition over time

In this section the analysis is carried out comparing species composition between the two time periods considered. It would have been more appropriate to perform the comparison among spatio-temporal strata resulting from the introduction of on-board technology (Chapter 2). However, two shortcomings arise to use these strata: 1) for FAD-fishing the third homogeneous time period (1997-2008) covers both observer programs, consequently it was decided to not combine both observer programs because the moratorium on FADs was implemented during the former, and 2) sampling was not done from November to January during the EU Bigeye program (and these months include the first FAD-fishing strata defined in Chapter 2). Thus the spatio-temporal strata obtained in Chapter 2 are used only to described occurrences and the respective probability of occurrence by species groups. In the case of free-swimming schools, the EU Bigeye program and the DCF program lie in the second and in the third homogeneous time periods evidenced in Chapter 2, respectively. Here, an occurrence was defined as a species group reported in a set on FAD or in free-swimming school, i.e., each group can occur once per set. The probability of occurrence was the ratio between the numbers of sets which a species group was present and the total number of sets observed by stratum.

Changes in species composition between observer programs are evaluated through a dissimilarity-based test for homogeneity of multivariate dispersions (PERMDISP; Anderson 2006). Variability in species composition among sampling units within a given spatial or temporal extent may be defined as β diversity (Anderson et al. 2006). PERMDIST test is an extension of the univariate Levene's test for homogeneity. Unlike the traditional likelihood-based test for differences in multivariate dispersions, the PERMDISP test is not sensitive to the lack of normality and allows using any multivariate measure based on pairwise resemblances (similarity, dissimilarity or distance) among sample units. The sample unit here was the fishing trip. Different dissimilarity measures have different properties, emphasizing different aspects of community data and therefore can yield different results. Consequently the selection of the dissimilarity measure depends in the ecological hypothesis. Because of the objective of this section, it was chosen the Euclidean distance including joint absences on presence/absence data. This solution has shown to provide great resolution for measuring changes in communities where many species are either rare or narrowly distributed (Anderson et al. 2010). Once the dissimilarity measure is selected, the

PERMDISP test is carried out by applying one-way ANOVA on the Euclidean distances $\Delta(.,.)$ from individual points (fishing trips) within a group (e.g. EU Bigeye) to their group median (centroid), $z_{ij}^{m} = \Delta(x_{ij}, m_i)$, where, x_{ij} is the vector which denotes the jth observation in the ith time period (EU bigeye/DCF) in the multivariate space of p variables (species). Therefore, the larger the distance to centroid, the larger the variability in species composition among samples.

Due to the misidentification at species level, mostly during first period, PERMDIST was carried out first at family level considering all species reported. It has been shown that differences in multivariate dispersions at the species level are maintained up to families (e.g. Terlizzi et al. 2009). The test was performed using only occurrences when individuals were identified at a species level to corroborate family results. This first attempt gives an overall picture of the heterogeneity in species composition of each fishing mode between both periods. However, this overall picture may hide changes in species composition by groups, e.g. a decrease in number of sharks species may be compensated by the increase in billfish species. In consequence PERMDIST was performed by species group using occurrences of individuals identified at a species level.

4.2.3 Species richness

Estimating species richness aids to describe community and regional diversity. In this study this indicator is utilized to describe the assemblage associated to each fishing strategy, and to allow a comparison between periods of time. We estimated first the overall number of species reported in both periods and then by species groups. Due to the characteristics of the method whose objective is to estimate an unknown number of species in the population from a limited number of samples, billfish and turtle groups are not analyzed because the total number of species of these groups present in the Atlantic Ocean is already known.

The analysis is carried out by means of sample-based rarefaction curves, a method which accounts for natural levels of sample heterogeneity (patchiness) in the data and uses incidence data (Gotelli and Colwell 2001). Rarefaction curves are plots of the expected species richness as a function of the numbers of individuals or samples (Gotelli and Colwell 2001). Let M samples and S species from a sampling period of time and m samples and s species from other sampling period. Both periods may differ in number of samples ($M > m$) and usually in number of species present (typically $S > s$). A rarefaction curve is produced by re-sampling randomly without replacement the pool of M samples, giving the average number of species represented in 1, 2,…M samples. Thus, rarefaction generates the expected number of species in a small set of m samples drawn at random from a large set of M samples.

A rarefaction curve typically rises relatively rapidly at the beginning, and then increases more slowly in later samples as new rare taxa are increasingly added, to reach eventually an asymptote when no further taxa are added. Notice that the asymptote is not always reached (notwithstanding if some species were not detected by the set of samples) and in such a case it is possible to estimate the curve asymptote by extrapolation approaches (Colwell et al. 2004). Estimating this asymptote would be relevant because the ICCAT has a bycatch list which includes 242 species that have been reported as caught in all tuna fisheries (e.g. longline, pole-and-line, purse seine). This list does not specify the species catches, nor the number of individuals caught (http://www.iccat.int/en/bycatchspp.htm). Although, not all the species in the list have been reported as bycatch by purse seiners, this list gives insight on the total number of species that can be captured by this fishery. Thus estimating the asymptote may indicate how many species can potentially be caught by purse seine fishing modes. In such a context, non-parametric richness estimators require no assumptions about an underlying species abundance distribution and do not require the fitting of either *a priori* or *ad hoc* models (Colwell and Coddington 1994). Indicators for incidence data such as: Chao2, Jacknife1, Jacknife2, and Bootstrap (See **Table 4.1** for details) were estimated and compared with the number of observed species (richness) during both historic periods. It was decided to collect the total species reported in both periods of years because the fact that one species was reported only in one of the two periods does not mean that it will not occur again.

Table 4.1 Summary of the species richness estimators used to estimate the asymptote of the sample-rarefaction curve.

Species richness estimator	Description
$S_{Chao2} = S_{obs} + \frac{q_1^2}{2q_2}$	This is a robust estimator based on the number of rare species (Chao 1984). S_{obs} is the number of species observed, q_1 is the number of species that occur in only one sample (singletons) and q_2 is the number of species that occur in exactly two samples (doubletons).
$S_{jackknife1} = S_{obs} + q_1\left(\frac{m-1}{m}\right)$	Burnham and Overton (1979) derived a series of jackknife estimators. Using the jackknife technique reduces the underestimation of the true number of species in an assemblage. For a set of *m* replicate incidence samples, the *k*th order jackknife reduces the bias by estimating richness from all sets of *m-k* samples. First-order jackknife (Jackkinfe1) is based on the singletons in the samples.
$S_{jackknife2} = S_{obs} + \left[\frac{q_1(2m-3)}{m} - \frac{q_2(m-2)^2}{m(m-1)}\right]$	The second-order jackknife estimator like Chao2 is based on the singletons and doubletons in the samples.
$S_{bootstrap} = S_{obs} + \sum_{i=1}^{S_{obs}}(1-p_i)^m$	Smith and van Belle (1984) derived this estimator using the bootstrap technique. This bootstrap estimate of species richness is based in the frequency of species *i*.

4.2.4 Spatial distribution of threatened bycatch species, and sets associated with whales and shark whales

In order to evaluate where the impact of the tropical tuna purse seine fishery on the epipelagic ecosystem may be more pronounced, high incidental species in the bycatch which also are classified at least as “vulnerable” in the IUCN red list, were selected to show their spatial occurrences, per fishing mode. These “vulnerable” or “endangered” species were gathered by large groups e.g., from 6 shark species with high occurrence only: silky shark (*C. falciformis*), scalloped hammerhead (*Sphyrna lewini*), oceanic whitetip shark (*C. longimanus*), and smooth hammerhead (*S. zygaena*) are listed as “near threatened”, “endangered”, and “vulnerable”, were termed as “Sharks”. The same classification was done with the species of Rays, Billfishes, and Turtles.

In all analyses realized in the previous chapters of this thesis, based on tuna species composition and tuna sizes, sets associated to whales and to whale sharks have been classified as free-swimming school sets and FADs sets, respectively. However, the aim in this section is to describe in detail patterns and the spatial distribution of these associations, since change in fishing strategies or new time-area closures may reallocate the spatial distribution of the purse seine fleet and as a result may have consequence on the impact of purse seine fishery on these two large species.

4.3 Results

4.3.1 Impact of the fishing strategies over time on the bycatch species composition

Performing PERMDIST test for both species and families did not depict changes in the variability of the species composition among samples (i.e. fishing trips) between the 2 periods analyzed whatever the fishing mode (**Table 4.3**). Changes in species composition by species groups showed similar patterns, except for sharks caught incidentally on FADs and rays caught on free-swimming schools. In both groups of chondrichthyan the species composition was higher (i.e. high average distance to centroid $\bar{d}_{cen}$) during the first period (1998-1999) than during the second one (2005-2008).

The average distance to centroid also reflects how high, or low, is the species composition among fishing trips. For instance, when all species were used in the analysis, FAD-fishing depicted the highest value with respect to free-swimming schools; i.e. more diversity is observed on FADs than on free-swimming schools. Among the other groups, bony fishes in both fishing modes presented the highest values, while the lowest values corresponded to rays and turtles caught on FADs, and minor tunas and turtles caught on free-swimming schools.

Table 4.3 Multivariate dispersion ($\bar{d}_{cen}$) based on the Euclidean distance of presence/absence of bycatch species groups for FAD-fishing and free-swimming schools, including results of PERMDIST test to compare between EU Bigeye and DCF observer programs.

FADs

	$\bar{d}_{cen}$ EU Bigeye	$\bar{d}_{cen}$ DCF	*df*	Sum Sq	Mean Sq	*F*	Pr(>*F*)
All families	1.745	1.72	1	0.0124	0.012369	0.0722	0.801
All species	2.435	2.376	1	0.0632	0.063172	0.5006	0.491
Minor tuna	0.7274	0.5617	1	0.5177	0.51773	1.7485	0.195
Sharks	0.8706	0.6864	1	0.6397	0.63974	4.6977	0.023
Rays	0.3049	0.2121	1	0.1622	0.16221	0.7887	0.376
Billfish	0.7347	0.7683	1	0.0213	0.021305	0.1438	0.712
Turtles	0.3764	0.3156	1	0.0697	0.06969	0.2552	0.573
Bony Fishes	1.788	1.843	1	0.0567	0.056675	0.8381	0.365

Free-swimming schools

	$\bar{d}_{cen}$ EU Bigeye	$\bar{d}_{cen}$ DCF	*df*	Sum Sq	Mean Sq	*F*	Pr(>*F*)
All families	1.758	1.613	1	0.3874	0.38744	2.5428	0.124
All species	2.009	1.92	1	0.1452	0.1452	0.4737	0.522
Minor tuna	0.3843	0.2623	1	0.2931	0.29314	1.0911	0.309
Sharks	0.5958	0.371	1	0.9962	0.99623	2.7419	0.1
Rays	0.695	0.4493	1	1.19	1.19	4.4805	0.038
Billfish	0.7547	0.6552	1	0.1954	0.19539	1.4288	0.237
Turtles	0.4057	0.487	1	0.1304	0.13041	0.3996	0.506
Bony Fishes	1.196	1.114	1	0.1336	0.13356	0.3685	0.549

Bearing in mind the spatio-temporal strata evidenced in Chapter 2, for FAD-fishing during the first period (1997-1999) from July to October, the largest number of sets was observed in this stratum (227), and logically the highest occurrences (**Figure 4.1**). Note that this stratum corresponds to the months before the moratorium on FADs months (November-January). In each temporal stratum bony fish was the species group with the larger number of occurrences than the other groups (**Figure 4.1**). Sharks, billfishes and minor tunas occurred to almost half-fold lower than bony fishes. In spite of each species group yielded differences in the number of occurrences among temporal strata, the probability of occurrence in bony fishes (~0.85) and billfishes (~0.4) remained similar in each temporal stratum, minor tunas decreased their probability of occurrence from January to October, while for sharks the peak of the probability of occurrence (~0.4) was from April to June (**Figure 4.1**).

During the second period (2005-2008), a high number of sets was observed from November to December and from April to June, and consequently similar pattern in terms of occurrences. In each temporal stratum bony fishes like during first period presented the higher occurrences (~0.9) and probability of occurrence than the other species groups. Minor tunas, billfishes, and sharks presented a probability of occurrence lower than 0.5 each. The lowest probabilities of occurrence were presented by rays and turtles (<0.1).

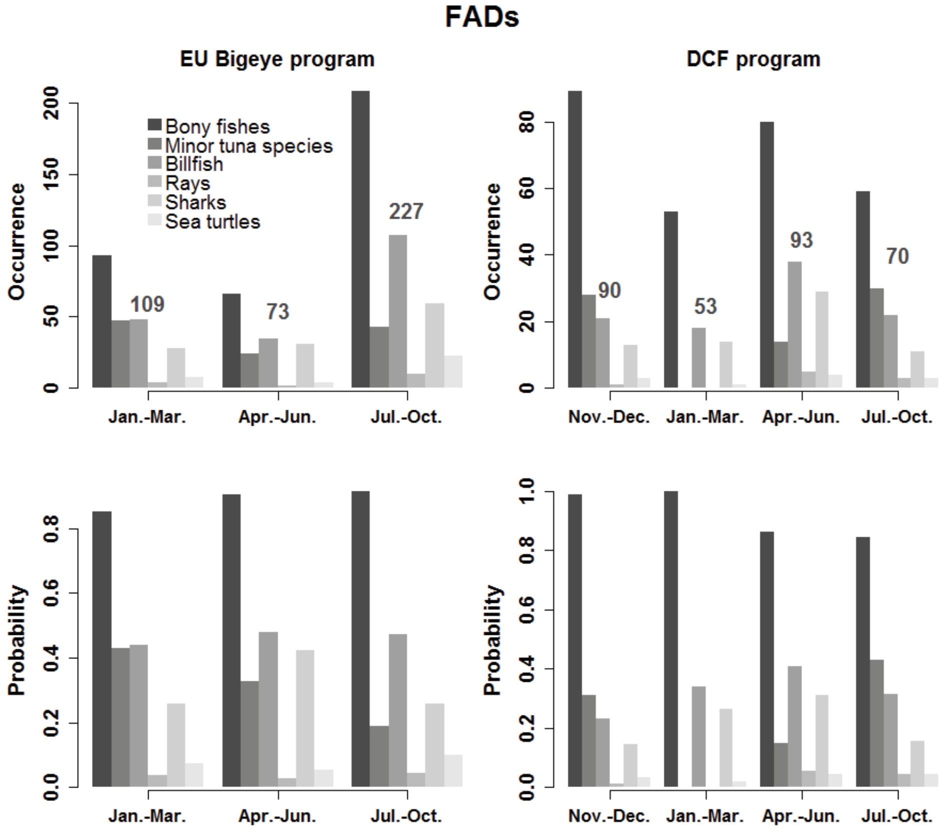

Figure 4.1 Observed occurrences (upper) and probability of occurrence (bottom) of species groups for each temporal FAD-fishing stratum during the third homogeneous time period (1997-2008) obtained in Chapter 2. Numbers above the bars correspond to the number of sets.

For free-swimming schools the temporal strata correspond to the second (1988-2002) and third (2003-2008) homogeneous time periods obtained in Chapter 2. During the first period (1997-1999) the highest species group occurrences were observed from June to October (third stratum), dominated by bony fishes, while the lowest occurrences were observed from November to March (first stratum); here dominated by billfishes (**Figure 4.2**). The numbers of sets in each stratum were 234 and 105 respectively. During April-May occurrences of species groups varied between 20 and 40. From June to October the probability of occurrence of bony fishes, minor tunas, billfishes, and sharks ranged between 0.3 and 0.5 (**Figure 4.2**). Billfishes presented the highest probability of occurrence (~0.7) from November to March.

Over the second period (2005-2008), the different strata depicted similar patterns of occurrence. Billfishes and bony fishes were the groups most frequent with the highest values from June to September. The probability of occurrence for billfishes remained similar among strata (>0.5). Bony fishes probabilities of occurrence ranged from 0.3 to 0.4. Minor tunas, sharks, rays and turtles depicted probability of occurrences of less than 0.2 each (**Figure 4.2**).

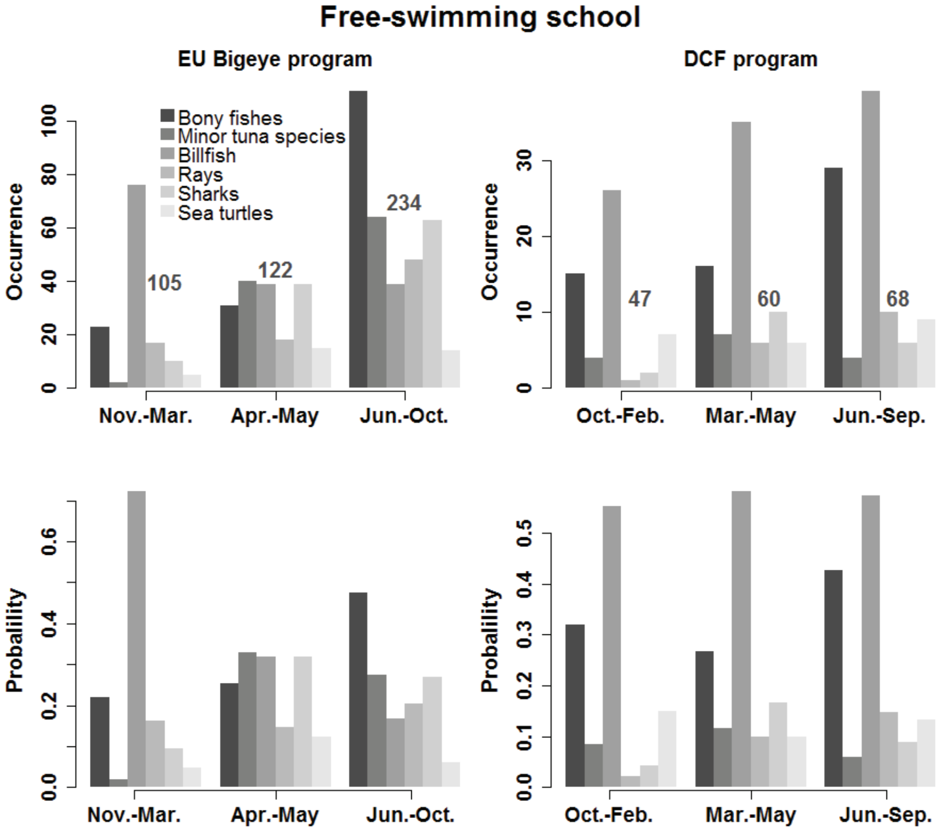

Figure 4.2 Observed occurrences (upper) and probability of occurrence (bottom) for species groups for each temporal free-swimming school stratum during the second (1988-2002) and third (2003-2008) homogeneous time periods obtained in Chapter 2. Numbers above the bars correspond to the number of sets.

4.3.2 Species richness over time

During the first period (1997-1999) the species observed were 49 species and 45 species on FAD-fishing and on free-swimming schools, respectively (**Table 4.4**). In the second period (2005-2008) 47 species were reported on FAD-fishing, and 45 species on free-swimming schools. Moreover, 57 species were reported on FAD-fishing during both periods, and 56 species on free-swimming schools, i.e. some species were caught during the first period and not during the second, and vice versa.

The sample-based rarefaction curves for FAD-fishing followed a similar pattern whatever the period (**Figure 4.3**). It should be stressed, however, that both curves did not reach the asymptote which means that on FAD-fishing there are species that have not yet been caught or reported. Despite the same number of species observed in free-swimming schools, the curve of the second period ends above the first one (**Figure 4.3**). This suggests that more species could have been caught during latter period than the former. Estimates of the asymptote suggest that for FAD-fishing a maximum of 87 species (Bootstrap and Chao2 indicators, **Table 4.4**) could be caught by purse seiners; a larger number compared to free-swimming schools (66 with the Jackknife2 indicator) species could be caught.

In the case of sharks caught on FADs the lower position of the rarefaction curve during the second period suggests a significant decrease in species richness. In contrast to the first period for which it seems that more shark species could have been caught, we can infer from the asymptote reached during the second period that few new species could be caught. Estimates of the asymptotes suggest that up to 11 species (Jackknife2) could be potentially caught by this fishing mode. With regard to free-swimming schools, the curves did not reach the asymptote but as described for FADs the second period curve ended beneath the first one. Estimates of the asymptote suggest that up to 11 shark species could be caught in free-swimming school sets.

Five species of rays were reported in each period on FADs, and a total of 6 species were caught during both periods (**Table 4.4**). None of the curves reached their respective asymptotes and consequently species richness cannot be estimated properly. In addition the curves grow slowly, suggesting that rays are species rarely caught on FADs. In free-swimming schools 4 species were reported during first period and 5 in the second. In opposite to FADs sets, both rarefaction curves seem to reach the asymptote, and the rapid growth shape of the curves means that rays frequently occurred in this fishing mode. Since asymptotes were reached we assume that there are not species uncaught.

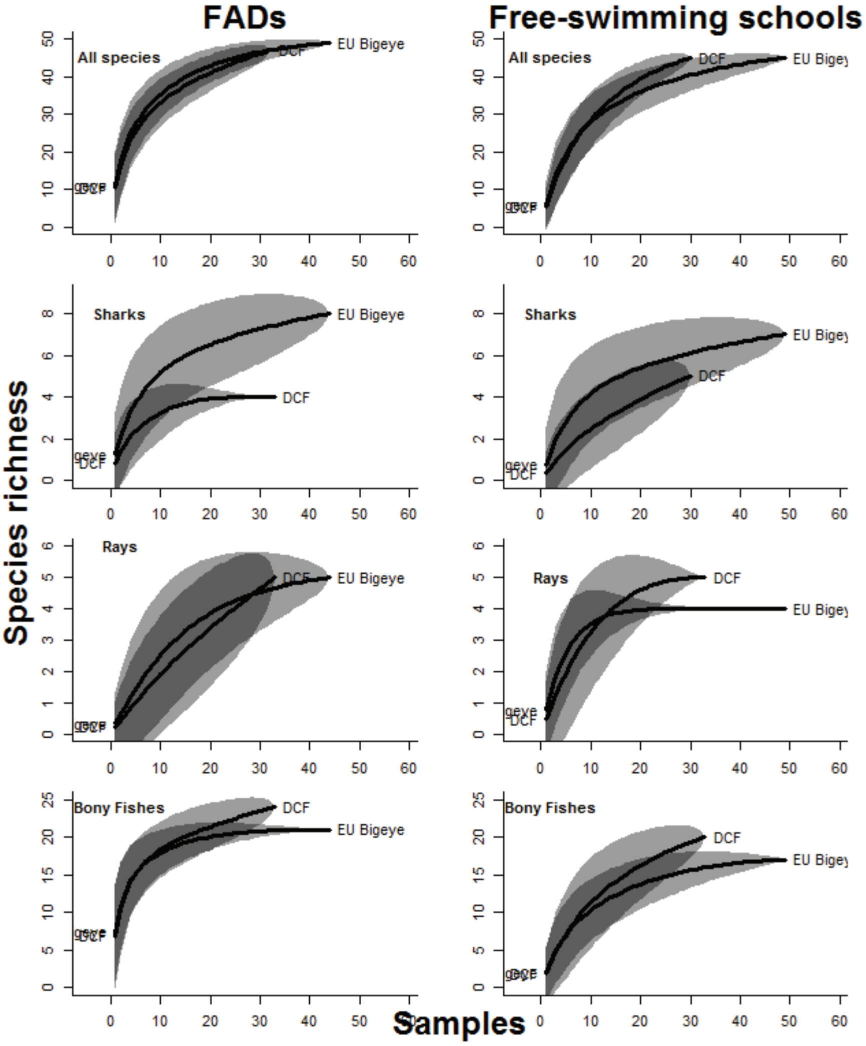

Figure 4.3 Sampled-based rarefaction curves comparison between periods of years for all species and by species group and by fishing mode (FAD-fishing and free-swimming schools).

21 species of bony fishes were reported in FAD-fishing during the period 1997-1999, 24 species in the late 2000s and a total of 27 species over both periods (**Table 4.4**). Both curves rise faster than for other species groups, evidencing that bony fishes species frequently occur on FADs. Estimates of the asymptote (from the Jackknife2 indicator) showed that bony fishes caught could be up to 37 species. The same situation was found in free-swimming schools, that is to say less species were detected during the first period than during the second (17 vs. 20 species), and a total of 25 species was observed for the two periods combined. It should be stressed, however, that none of the periods reached their respective asymptote (**Figure 4.3**). Both rarefaction curves grow slowly, suggesting that not all bony fishes species are systematically caught in free-swimming schools. Estimate of the asymptote suggests that up to 30 species (Jackknife1) of bony fishes could be caught on free-swimming schools.

Table 4.4 Species richness observed during each period and for the overall. Estimates of the species richness asymptotes and the corresponding standard errors from Chao2, Jackknife1, Jackknife2, and Bootstrap estimators.

FADs

	Species EU Bigeye	Species DCF	Total	Chao	Chao.se	Jack1	Jack1.se	Jack2	Boot	Boot.se	n
All species	49	47	57	87.3	28.7	67.9	3.6	76.6	61.6	1.9	76
Sharks	8	4	8	10	3.7	9.9	1.4	10.9	8.9	0.9	76
Rays	5	5	6	6.5	1.3	6.9	0.9	7	6.6	0.7	76
Bony Fish	21	24	27	27.0	0	31.9	2.6	36.8	28.9	1.3	76

Free-swimming schools

	Species EU Bigeye	Species DCF	Total	Chao	Chao.se	Jack1	Jack1.se	Jack2	Boot	Boot.se	n
All species	45	45	56	61.1	4.4	64.9	2.9	65.9	60. 8	2.03	79
Sharks	7	5	7	7	0	8.9	1.4	10.9	7.8	0.7	79
Rays	4	5	6	6	0	6	NA	5.04	6.2	0.4	79
Bony Fish	17	20	25	26.8	2.2	29.9	2.6	28.1	27.9	1.8	79

4.3.3 Species listed as threatened in the IUCN red list

As mentioned earlier, some bycatch species caught by purse seiners are listed in the IUCN Red List of Threatened Species. In this section we selected only the species with a high incidence in each of the two observer programs. All the species selected were most frequently during the late 1990s than during the late 2000s (**Table 4.5**). For sharks (this group showed the highest incidences of all species groups), silky shark (Near Threatened) was the species with the highest occurrence from the four shark species listed by IUCN, and was mainly associated with FADs during both time periods (**Table 4.5**). The scalloped hammerhead (*Sphyrna lewini*) is the only species of shark listed as endangered from the overall shark species reported in both periods. This species occurred most of the time on free-swimming schools sets during first period. The bycatch of these species on FADs were mainly north Picolo area and the Cape Lopez area, while bycatch of free-swimming schools was inshore near to Liberia and Senegal (**Figure 4.4**).

In the group of rays, the giant manta (*Manta birostris*) and the devil fish (*Mobula mobular*) are listed by IUCN as vulnerable and endangered respectively. Both species were present in purse seine bycatch during both periods, but the highest occurrences were found in free-swimming schools during the first period (**Table 4.5**). FAD-fishing and free-swimming school bycatch of these species was mainly above 5° N latitude near to the African west coast (**Figure 4.4**).

Table 4.5 Main species listed by the IUCN and caught incidentally by purse seiners during EU Bigeye and DCF programs. Occurrence observed is showed by fishing mode (FADs and Free-swimming schools -FS)

				FADs		FS		Total
Species group	Common name	Species	IUCN Status	EU Bigeye	DCF	EU Bigeye	DCF	
Sharks	Silky shark	*Carcharhinus falciformis*	Near Threatened	65	53	32	1	151
	Oceanic whitetip shark	*Carcharhinus longimanus*	Vulnerable	13	4	4	2	23
	Scalloped hammerhead	*Sphyrna lewini*	Endangered	6	0	16	4	26
	Smooth hammerhead	*Sphyrna zygaena*	Vulnerable	9	3	27	7	46
Rays	Giant manta	*Manta birostris*	Vulnerable	4	4	16	2	26
	Devil fish	*Mobula mobular*	Endangered	2	1	22	4	29
Billfish	Atlantic blue marlin	*Makaira nigricans*	Vulnerable	80	66	23	17	186
Turtles	Loggerhead turtle	*Caretta caretta*	Endangered	11	1	14	2	28
	Leatherback turtle	*Dermochelys coriacea*	Critically Endangered	3	1	12	2	18
	Olive Ridley turtle	*Lepidochelys olivacea*	Vulnerable	5	5	0	7	17

For billfishes (the second group with high occurrence among species groups), the Atlantic sailfish (*Istiophorus albicans*) and the Atlantic blue marlin (*Makaira nigricans*) were the main bycatch species. The former species, whose status in the IUCN list is unknown, has mainly occurred on free-swimming schools. The latter is listed as vulnerable and has mainly been caught on FADs (**Table 4.5**). This species was caught along the equator to 25°W longitude and between the equator and 15°N latitude, while in free-swimming schools bycatch was mainly located in the Cape Lopez area, N. Equator area and NW Picolo area (**Figure 4.4**).

Six species of sea turtles were caught incidentally by purse seiners and they are listed in the IUCN; three are critically endangered, two endangered and one vulnerable. Even if turtle observer data may be analyzed with caution due to the potential bias in non-detection of entangled individuals in the webbing that fishers frequently attach under FADs, sea turtles caught during observer programs were apparently the group with the lowest occurrence among all species groups (**Table 4.5**). The loggerhead turtle and the leatherback turtle occurred mainly on free-swimming schools sets and their spatial distribution was similar to that observed for the Atlantic blue marlin associated with the same fishing mode (**Figure 4.4**).

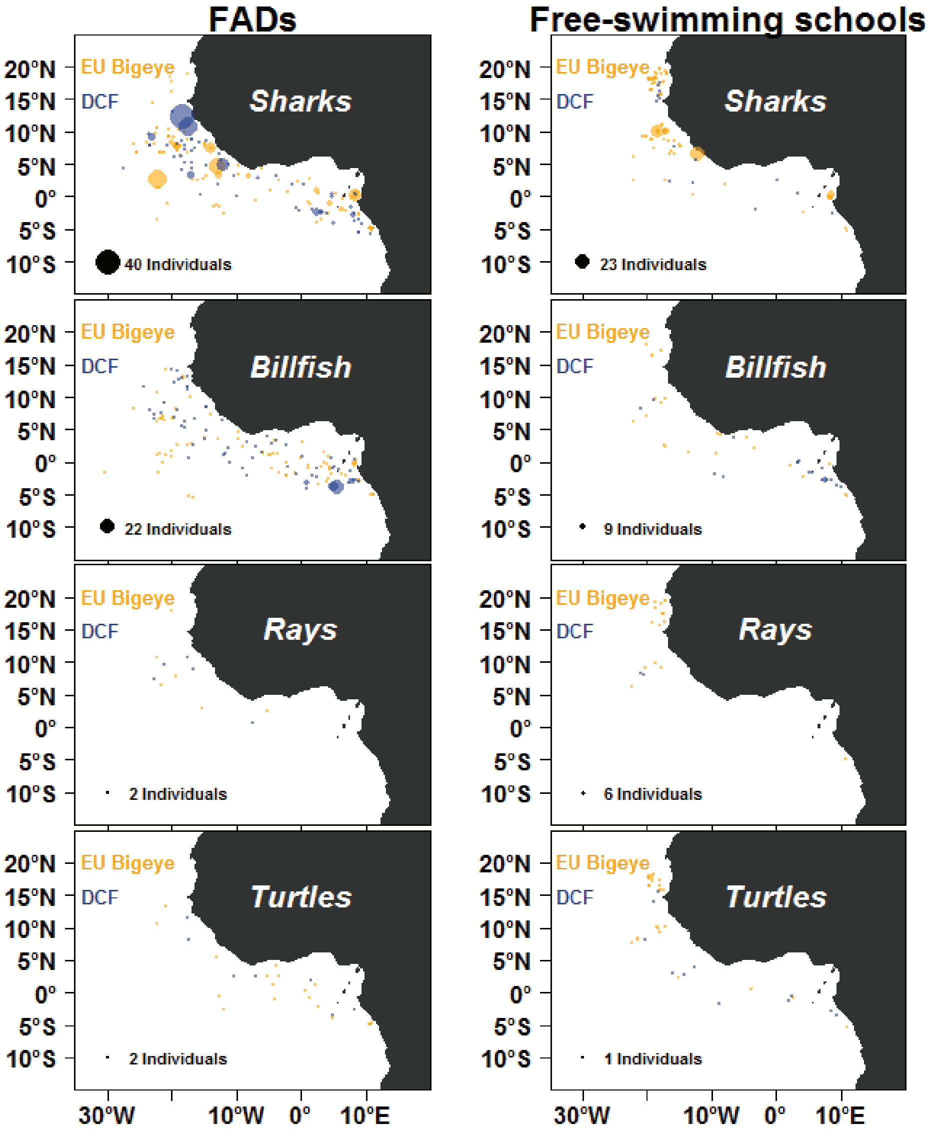

Figure 4.4 Comparison of the spatial distribution of the main species groups (sharks, billfishes, rays and turtles) caught incidentally during the EU Bigeye (orange bubbles) and DCF (blue bubbles) programs by fishing mode (FADs and free-swimming schools). The number of individuals is given only as reference due to the reasons explained in Methods section.

4.3.4 Sets on whales- and whales sharks-associated tuna schools

On average every year 8% of free-swimming school sets were exerted on whales and 9% of FADs sets on whale sharks. The annual time series for whale-associated schools sets never exceeded 15% of free-swimming school sets (**Figure 4.5**). The number of sets on whale sharks depicted a similar pattern than on whale-associated school sets, and reached its maximum value in 1996, being little bit more than 20% of FADs sets (**Figure 4.5**). Since 2000 both indicators yielded a decreased pattern.

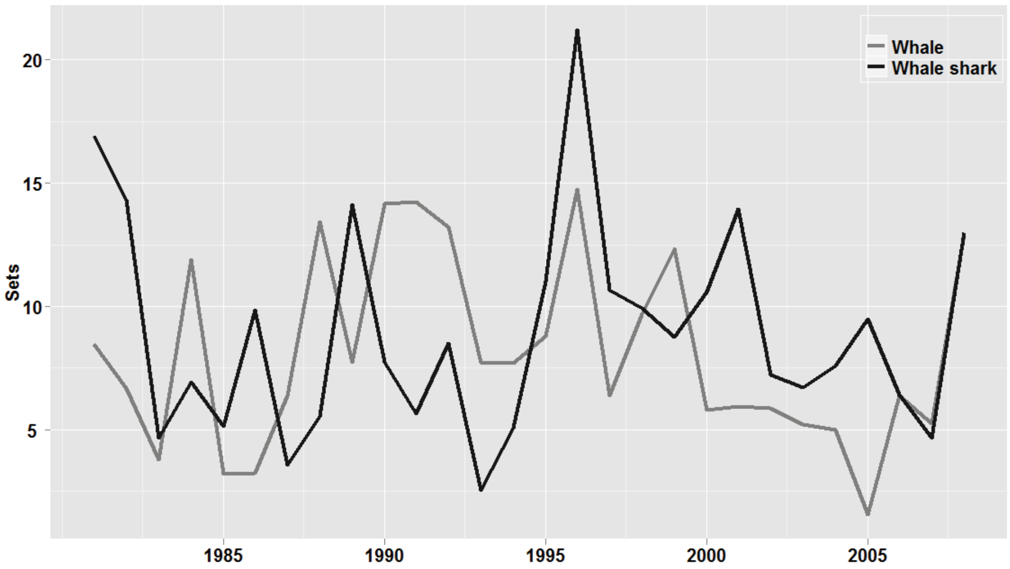

Figure 4.5 Percentage of sets made on whales (grey) and whale sharks (black) respect to free-swimming schools and FADs respectively.

Because both time series indicators depicted patterns without major changes over time, the total sets associated with whales and whale sharks reported in logbooks were grouped by quarters from 1981 to 2008. During the second and third quarters of the year more sets were made than during the first and four quarters whatever the type of associations. During the first quarter, whale-associated schools sets mainly occurred along the equator among Picolo area, N. equator, and S. equator, while only 6 sets on whale shark were reported (**Figure 4.6**). In the second quarter, sets on whales were made along the African west coast, from Cape Lopez area to Senegal area, while sets on whale sharks were concentrated near Gabon within the Cape Lopez area (**Figure 4.6**). In the third quarter, sets on whales were reported and distributed inside the Gulf of Guinea, mainly in N. equator area and Cape Lopez area, while sets on whale sharks depicted the same pattern as previous quarter and. During the fourth quarter, sets on whales were reported mainly along and above the equator within Picolo and N. equator areas, while 62 sets on whale sharks were mainly made in Picolo area and along the African west coast within Cape Lopez area. Notice that the seasons with high number of sets on whales and whale sharks did not correspond to the months of the moratorium on FADs (i.e., November-January).

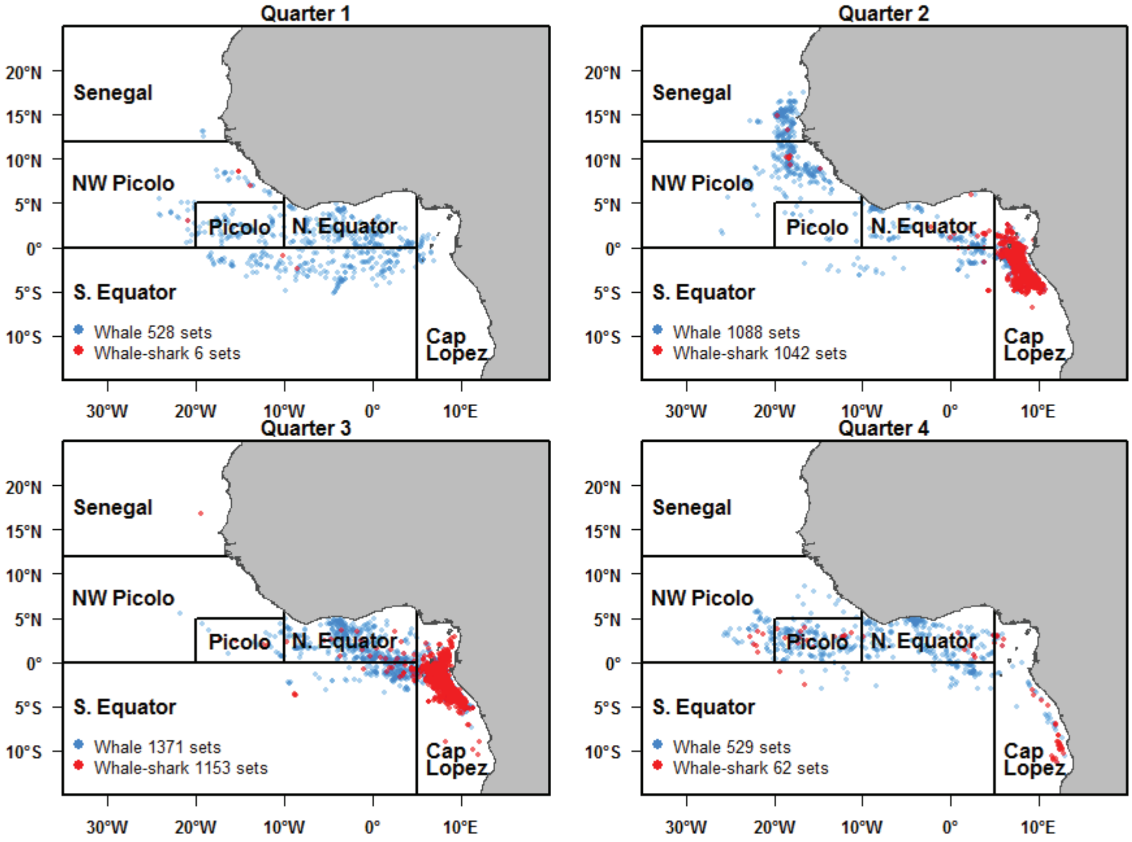

Figure 4.6 Quarterly spatial distribution from logbooks data of sets made by French purse seiners on whales and whale sharks from 1981 to 2008. The total number of sets in each association during each quarter is indicated.

4.4 Discussion

After the dolphin-tuna problem in the eastern Pacific Ocean (EPO), the introduction of FAD-fishing became a conservation issue in tuna purse seine fisheries. Nevertheless, fishing on free-swimming schools also generates bycatch, although a lesser extent than observed on FAD-fishing. Because any change in target species/size category or any regulation measure is reflected directly by a change in fishing strategy, and consequently affect quantitatively and qualitatively bycatch, we analyzed the effects of both purse seine fishing modes on the bycatch between two periods of time, characterized by the EU bigeye and DCF programs. During the first period the species occurrences were higher than second period, but the overall species composition variability between periods did not depict changes in both fishing modes. However, sharks caught on FAD-fishing and rays caught on free-swimming schools depicted changes in species composition variability. Analyzing species richness from rarefaction curves showed that some species are likely undetected or uncaught. The silky shark and the Atlantic blue marlin were the species most caught incidentally among the threatened species listed by the IUCN and whatever the accuracy of their status they could be use as totem species by environmental NGO. Regarding the tuna schools associations with whales and whale sharks no annual trend has been detected but they showed marked seasonality, both in the number of sets and areas covered.

4.4.1 Effects of fishing strategies on bycatch species composition

Ours results suggest that in general the species assemblages caught by EU purse seiners have not changed, in spite of the increasing use of FADs fishing, from the first period to the second. However, due to heterogeneity in the objectives of the observer programs and in the resulting bycatch data, the analysis was carried out using only presence/absence data and including joint absence. It should be noted however that this combination provides great resolution for measuring changes in communities where many species are either rare or narrowly distributed (Anderson et al. 2010). However, a variety of dissimilarity measures may be used to highlight different properties of ecological data, for instance, using species abundances may be useful to assess species composition focusing on phenomena that can cause changes in total abundance, rather than in proportion. This is relevant because in both fishing modes not all species are caught in the same magnitude and some of the species occurred only few times (Chassot et al. 2009; Amandè et al. 2011). Thus using abundance instead presence/absence would have been more appropriate to assess possible changes in species composition variability, specifically if catches of some species have been reduced. Unfortunately, as mentioned above, bycatch data were reported sometimes in numbers of individuals, sometimes in weight, thus it was difficult to estimate abundance.

As mentioned earlier, fishermen behavior at sea and the use of new fishing technology may modify the degree of bycatch. Fishermen could avoid some spatio-temporal strata with high bycatch rates. They could modify the fishing gear to reduce incidental catch, improve the setting process, avoiding/reducing the bycatch (Hall 1996). This behavior may be complemented with regulations, banning some gears, areas and/or seasons. From this study it may be argued that the presence of moratorium on FADs led fishermen to increase FADs sets during the previous temporal stratum (July-October), resulting in high occurrences of species groups. Unfortunately there were no observer data during the moratorium and before the moratorium implementation (e.g. during the early 1990s) to compare the bycatch with previous months or years. However as showed in Chapter 3, there was a reduction in the number of sets on FADs consequently a reduction of bycatch amounts may have been achieved. Gaertner et al. (2002) showed by simulations on the bycatch of billfishes caught by the EU purse seine fleet in the presence of the moratorium on FADs that the bycatch of marlins was reduced, while sailfishes catch was increased due to the report of the effort on free-swimming schools. This reflects that changing fishing strategy may lead to affect other epipelagic species. Our results are in agreement (at least for bony fishes, billfishes and minor tunas species) with the seasonal estimates of Amandè et al. (2010) on bycatch caught on FADs by the EU purse seine fleet in the eastern Atlantic Ocean which suggest that the larger bycatch amount occurred during the second half of the year. Unfortunately before EU Bigeye program there were not available data with enough information to carry out a BACI approach like in Chapter 3. The effects resulted from the fishery expansion westward during the second period obtained in Chapter 2 related with FAD-fishing was not possible. For this reason we only used the third period's temporal strata which covered both observer periods of time.

Another important aspect related to bycatch in the Atlantic Ocean is the local market of "faux poisson" in Abidjan (Côte d'Ivoire). Landings of this byproduct have fluctuated since the early 1980s with an increasing trend recently, from around 8000 t in 2003 30000 t in 2009 (Chassot et al. 2009; Chavance et al. 2011). The "faux poisson" landed by the EU purse seiners, was mainly composed by undersized skipjack and by minor tunas (Chavance et al. 2011). For the French purse seine fleet only, Chassot et al. (2009) estimated "faux poisson" at 154 kg per ton of skipjack landed (3.5 times the discard rate estimated for FADs); for comparison yellowfin was at 15 kg per ton of yellowfin species landed in canneries. In such a context, under the existence of this local market by obtaining an extra income for bycatch, fishermen could be encouraged in such a level to not entirely avoid bycatch.

Fisheries management has been changing from a single-based regime towards an ecosystem-based fishery management (EBFM). This approach encourages taking into account the bycatch in management to maintain biological diversity (Garcia et al. 2003). Within this framework, due to the nature of tropical tuna purse seine fisheries, they cannot be assessed only in terms of tuna catch (Gaertner et al. 2002). Our findings contribute to understanding the impacts of the main fishing modes deployed by tuna purse seiners in the tropical Atlantic Ocean. Tuna-fishing affect the abundance of epipelagic species directly generating bycatch and indirectly the predator-prey relationship in the food web.

According to the ICCAT bycatch list, the purse seine gear (including temperate fisheries) has interacted with 75 species. We showed that the EU tropical purse seine fleet has reported the capture of 65 species over the two periods of time. However, as mentioned previously, a total of 242 species are reported in the ICCAT bycatch list. Even if most of these species have been caught by longliners (Arrizabalaga et al. 2011), these species could potentially be caught by purse seiners. The species richness observed in each fishing mode was similar, although it was expected to find more species in FAD-fishing than in free-swimming schools. This not necessarily implies that fishing on free-swimming schools has the same impact in bycatch. We only used individuals identified at species level, due to misidentification of some species it is possible that more species were not reported or grouped at family level, mainly in FAD-fishing, which presented more diversity than free-swimming schools (e.g. see the lower values of the distance to centroid from PERMDIST test, and the slow growth pattern in almost all rarefaction curves, both for free-swimming schools). In this sense, estimating species richness with the aid of the asymptote curves give an insight of how many species may potentially be caught by each purse seine fishing mode. The asymptotes estimated in FAD-fishing suggested that an overall of 87 species may be caught on this fishing mode, mostly bony fishes species, while in free-swimming school an overall of 66 species may be caught. However, the number of species recorded is likely to increase in the future as more fishing trips will be observed. It should be pointed that this analysis was performed on species presence/absence indicators, and the results did not implied that all species have been caught in high quantities. Moreover, extrapolating curves may be questionable when the "true" number of species is low, as showed in the case of rays.

As mentioned earlier, the EU tuna purse seine fleet operating in the Atlantic Ocean generates less bycatch than tuna or tuna-like species longline fisheries. For instance, sharks and billfishes bycatch by longliners targeting tuna correspond to 8.7% and 6.3% of the total catch respectively (Matsumoto and Miyabe 2000), while billfishes incidentally caught on longliners targeting swordfish represent 70.3% on the total catch (Mejuto et al. 2006). As an element of comparison in the EU purse seine fleet, billfishes and sharks represent 0.4% and 0.09% of the total catch (Amandè et al. 2010).

In terms of effects on the high seas ecosystem, large bycatches of top predators like billfishes and sharks could affect the upper trophic levels of the epipelagic ecosystem, leading to cascading effects on low trophic levels. Species with longer generation lengths (i.e. measure of reproductive turnover) would be expected to take longer to recover from population declines. Compared with most IUCN-assessed bony fish, the proportion of supposed threatened species of billfishes is high, similar to other valuable and long-lived species such as marine mammals, sea turtles, sharks, and rays (Collette et al. 2011). In the EU purse seine fleet in the Atlantic Ocean, Arrizabalaga et al. (2011) through an ecological risk assessment found that some sharks and bony fishes presented high risk values (i.e. the risk of being negatively impacted by the fishery). Among these species (most of them with relatively low productivity), we showed that during the second period most of them occurred in a lesser extent than during the first period. This may be due to the total number of fishing trips observed, changes in setting behavior of purse seiners, mainly avoiding schools with small size tuna (as suggested by Goujon 2004b), or abundance decreasing (Gerrodette et al. 2012). Moreover, among the species cataloged as threatened by IUCN and being caught by the EU purse seine fleet, only Atlantic blue marlin presented high occurrences. The other species with high occurrences are not catalogued as threatened. For instance, silky shark is near threatened and the status of the Atlantic sailfish is unknown. The decline in top predators may increase predators or herbivores in mid-trophic levels (mesoconsumers), affecting species that are eaten by them (Heithaus et al. 2008). For instance, in longliners surveys in the tropical Pacific documented up to 10-fold declines in catch rates of 12 large pelagic predators (tunas, billfishes and sharks) from 1950 to 2000 coincided with 10- to 100-fold increases in catches of pelagic stingrays (*Dasyatis violacea*) and other mesoconsumers over the same time period (Ward and Myers 2005). Recently, in the purse seine fishery in the EPO there was no evidence of decreasing trophic levels of landings and discards, and the same pattern was observed evaluating the replacement time of landings and discards on free-swimming schools and FADs (Gerrodette et al. 2012).

Regarding the objective of EBFM, it is encouraged improve fishing selectivity, reducing bycatch and impacts on long-lived species (sharks, turtles, marine mammals, birds), as well as on juvenile fish. In this sense, technological improvements have been suggested to mitigate bycatch and detrimental effects on fishing resources (Kennelly and Broadhurst 2002; Jennings and Revill 2007). In some fisheries, gear modifications have been introduced to reduce or eliminate the bycatch of untargeted species or non commercial size of the target species (Graham et al. 2007; Madsen 2007; Wade et al. 2009). In such a context, some efforts have been made to change technological gears and fishing procedures to reduce shark bycatch in tuna fisheries (Cosandey-Godin and Morgan 2011). The use of deterrents has been suggested, such as bait stations, and/or the use of sounds and chemicals that could lure sharks from FADs before setting (Kondel and Rusin 2007). Other efforts addressed to reduce the overall bycatch are restrictions on set times (e.g. setting in times of the day when non-tuna species are less concentrated beneath the FAD), restrictions on FADs sets and other floating objects (e.g. the moratorium on FADs in the Atlantic Ocean), using multiple FADs segregating certain species, and the use of biodegradable FADs designed to reduce the potential entanglement of bycatch species (Franco et al. 2011). However, some of these efforts are currently being conducted.

In the eastern Atlantic Ocean, ICCAT, besides the establishment of the time-area closures, has established some recommendations to reduce bycatch of sharks, billfishes and turtles. These recommendations have been directed to some specific species, such as hammerhead sharks, silky sharks, blue and white marlins, and sea turtles (recommendations [10-08], [11-08], [11-07] and [10-09], respectively). In spite of these efforts to accomplish the objectives of EBFM, these remain controversial to implement in fisheries management. Moreover, Murawski (2000) stood out the lack of consensus for defining overfishing ecosystem concept and suggested the need for objective metrics that gauge properties associated with the main features of the ecosystem. In this sense, encouraging fishing selectivity may also result in unexpected and undesirable impacts to fisheries and ecosystems (Zhou 2008, Garcia 2011). Therefore, it has recently been argued that a “balanced exploitation” might alleviate many of the ecological effects of fishing by avoiding intensive removal of particular components of the ecosystem, while still supporting sustainable fisheries (Zhou et al. 2010; Garcia et al. 2012). Balanced exploitation aims to distribute fishing pressure across the widest possible range of trophic levels, sizes and species, in proportion to their natural productivity, reducing fishing pressure where it is excessive (Garcia 2011). Zhou et al. (2010) suggested that research needs to this approach include sustainability assessments of non-target species, identification of vulnerable species, fishing gear design, study of better fishing strategies, and impact assessments that incorporate trophic feedback and potential evolutionary effects.

4.4.2 Fishing on whales and whale sharks

As mentioned earlier, whale sharks and cetaceans are particularly vulnerable to being encircled by purse seine nets, due to the propensity of tuna to form schools around them. Both type of sets showed marked seasonality, mainly sets associated with whale sharks. The major amount of sets associated with these species coincides with coastal and equatorial upwellings during second and third quarters, as well as the Canary upwelling with its spring maximum during second quarter.

These regions support high cetacean biomass, corresponding to the presence of large quantities of available food (Cayré et al. 1993). In fact, during early twentieth century a large whaling industry was present in the equatorial Atlantic region (Best and Allison 2010). Although in the logbooks is not specified the whales species, it has been reported sets associated with the baleen whale, sperm whale, fin whale and humpback whale (Cayré et al. 1993; Gaertner et al. 1996; Amandè et al. 2010). During sets on whales, the fishermen keep the whales inside the purse seine as long as possible, and whales often remain in the net until the end of pursing and then escape from the purse seine (Romanov 2002).

In the case of whale sharks sets, it is difficult to assess the mortality of this species by purse seining because sighting is the only information reported in logbooks. However, in the western and central Pacific Ocean it was reported that 12% of interactions with whale sharks resulted in mortality, and during 2009 there were 60 whale sharks deaths due to encirclement by purse seiners (WCPFC 2011). It is important to assess mortality of this species by tuna purse seiners due to the vulnerability to fishing pressure, mainly because whale sharks are found in low abundance, are highly migratory, and reach maturity late in life (Stevens 2007). Currently in the eastern Atlantic Ocean there are not management measures concerning fishing practices on whales and whale sharks.

4.5 Conclusions

The potential problems associated with bycatch and/or discards is extensive: threatening endangered species, wasting resources, increasing fishery costs, damaging habitat, impacting the food web and redirecting ecosystem pathways (Hall et al. 2000). Given sufficient investment in research and development, viable changes in fishing gear and methods are possible to reduce bycatch in tuna fisheries. While recognizing that long-term viability relies on the availability of tuna resources, voluntary action by the tuna fishing industry to reverse and prevent further overexploitation of tuna stocks and to address bycatch issues may be limited (Gilman 2011). While efforts of RFMOs to managing bycatch have been made, several gaps remain, and compliance by many member States is likely low.

However, research is only a small part of bycatch management. Reducing bycatch to sustainable levels will also require collaborative efforts among scientists, conservation organizations, resource managers and industry. Although the objective of reduce bycatch recently became controversial (e.g. balance exploitation; Garcia et al. 2012). Anyhow, collaborative effort must account for fisher behavior and decision making as well as an economic perspective where consumers play an important role by influencing market value and demand. Effective tuna fisheries management will require coordinated actions by RFMOs to develop a combination of technological improvements, changes in fishing practices, modification of fishing effort and international agreements that, together, can monitor and manage bycatch (Lewison et al. 2004).

Meanwhile, the management of FAD-fishing in the oceans of the world needs to be addressed as the potential negative effects of FADs, not only in terms of the tuna resource (i.e. the ecological trap effect; Hallier and Gaertner 2008) but also in terms of bycatch of vulnerable species, such as some shark species. The Indian Ocean Tuna Commission (IOTC), in an effort to know and control FAD-fishing, recently established for all purse seiners to provide the total number and types of FADs deployed by supply and purse seine vessel on a quarterly basis [Res. 10/02]. In the Pacific

Ocean, some “FAD management plans” focusing on data collection as well as FAD limitation have been developed while supply vessels have been banned from the EPO fishery since 1999 (IATTC 1999). In the Atlantic, based on the resolutions adopted by other tuna-RFMOs has recently been suggested to extend recommendation [11-01] related to operations on FADs on a mandatory basis to every supply vessels whatever their fishing flag, covering all the activities conducted by them (e.g. with detailed logbooks). Purse seine fishery management must extent observer programs for all contracting parties, including monitoring sets on whales and whale sharks to assess the effects on these species.

General conclusions

In this dissertation the dynamics of tuna purse seiners has been analyzed in order to (1) estimate the effects of the introduction of on-board fishing technology on their fishing strategies and tactics, and catchability, (2) study the adaptive responses of the fleets facing management measures, and (3) describe the effects of fishing strategies on bycatches. Due to some constraints in the availability of data the analyses were mainly carried out on the EU purse seine fleet, and the Mexican purse seine fleet was used only in the study of the adaptive responses to management regulations. The analyses were performed on the basis of a set of fishery indicators representing the fleet dynamics. The use of indicators reflects the state of the fishery system, especially the human system, and also allows monitoring the fishery. The purpose of indicators is to enhance communication, transparency, effectiveness and accountability of management of a highly complex fishery system (Garcia et al. 2000).

The increasing concern on stocks declining has led to the implementation of management measures to prevent overfishing. In established/mature fisheries, as depicted by tuna fisheries, these tools tend to focus in controlling fishing effort from stock assessment. However, controlling effort does not necessarily mean that fishermen behavior and fleet dynamics are taking into account. Consequently the unanticipated fishermen responses have led to failures in achieving the objectives of ensuring the conservation and utilization of stocks, and maintaining the stocks at or above levels capable of supporting maximum sustainable yields. In such a context, tropical tuna fisheries are more challenging than many other fisheries, owing to tunas are highly migratory and to different gears targeting tuna. Moreover owing the extent of the tropical Atlantic and Pacific oceans, carrying out surveys to obtain fishery-independent data is difficult and expensive. Consequently data will still depending in large part from fishermen (i.e. commercial catch) and any change in the fleet dynamics will modify the relationship between catch rates and abundance (i.e., the catchability), which is the basis for stock assessment and resulting management. The results in this dissertation highlight the relevance of including the dynamics of the fleet in the management system to improve fishery regulations.

Fishing technology investment is carried out continuously to increase benefits or saving costs. The approach used regarding the introduction of fishing technology on French purse seiners allowed observing the direct effects on fishing strategies, increasing fishing power, and indirect effects modifying the seasonal choices of the fishing grounds (tactics). The approach used allowed analyzing different temporal scales going from decades to spatio-temporal strata within each period of time. These results highlight the importance of monitoring the rate of investment in the fishery because the continued technological investments by purse seine fishing industry. We are aware that this type of analysis should be carried out with other purse seine fleets, because they may have different fishing practices, which will change the type of acquired technology, and because this new technology has not been introduced necessary at same time. As an example, Spanish purse seiners fish mainly on FADs while French purse seiners fish on both fishing modes but mainly on free-swimming schools. Analyzing all fleets will permit to obtain an overall picture of the fishermen behavior at sea and better understand changes in catch rates. It would be important that each country or the ICCAT encourage fishing industry to participate with scientist providing information concerning investment. In this sense the close cooperation with the French fishing industry, particularly ORTHONGEL and SAUPIQUET for accessing such valuable information has been important.

Unfortunately it was not possible carried out the same analysis with the Mexican fleet because the data did not include the time when the major technological investment was done. However, due to the tuna-dolphin issue, the fishing industry in the eastern Pacific Ocean (EPO) has contributed with scientist to monitoring purse seiners.

The major technological improvement during last 20 years in purse seine fisheries has been the development of FAD-fishing, increasing catch rates and decreasing the rate of unsuccessful sets. However, the captures of undersized and juvenile tunas have led ICCAT and IATTC to implement management measures to decrease these effects. Once again, the participation of fishing industry in the Atlantic Ocean allowed establishing the voluntary moratorium on FADs. Consequently a decrease in catches with FADs was observed, but it was difficult monitoring and achieving compliance from all fleets operating in this ocean, leading to illegal, unregulated and unreported fishing activities. The fishing effort reallocation is important to consider when define time-area closures, because it could lead to non compliance or exacerbating the fishing pressure outside the closed area. In this regard, the BACI approach allowed evaluating the effects of the time-area regulatory measures on the European fleet dynamics, and highlights the importance of taking into account for responses of fishermen. In this sense, the Mexican fleet in the EPO faced the season-length restriction reducing the time spent in port, ensuring more time at sea. It was showed however in our study that the response to regulation, and as a consequence the effectiveness of the measure, was dependent on the size category of the vessels. The establishment of spatio-temporal regulations is made usually in function of life traits of resources, notwithstanding complementing this information with fishermen behavior will lead to better management measures. Moreover, spatio-temporal regulations must be accompanied with other regulatory tools to avoid exacerbate fishing pressure outside the closed area or before arriving the closed season. Simulation analyses must be done to evaluate possible fishermen responses before implementing management measures. In this regard, the indicators used in this dissertation may be used as input data to perform simulations.

The continuous increasing use of FADs has generated concern about the effects on the epipelagic ecosystem, becoming a management problem. FAD-fishing generates bycatch mainly of sharks, billfishes, bony fishes, and in a lesser extent turtles and rays. Despite the bycatch produced by purse seiners is lower than in other fisheries (e.g. longliners, trawlers) and is used as a byproduct for the local markets, tuna purse seine bycatch contributes with depletion of top predators populations which may lead to food web issues. From the two observer data sets used, our results did not allow showing major effects on bycatch population or in the food web. However it gave an idea of the diversity and how many species may be caught by each fishing mode. Moreover except for sharks caught on FADs and maybe rays caught on free-swimming schools, the other species groups did not depict changes in species composition between the two periods considered (1998-1999 and 2005-2008). The decrease number of species occurrences during the second period may have been due to the lower number of fishing trips observed than during the first period or because an improvement of selectivity due to the use of electronic devices by skippers before setting. The results for bycatch species listed by the IUCN as threatened showed that they are not caught continuously (e.g. turtles, the scalloped hammerhead, or the smooth hammerhead). The bycatch species more caught are the silky shark, the Atlantic blue marlin and the Atlantic sailfish, only the second is considered threatened and the ICCAT has recently taken steps to reduce the bycatch of these species (recommendations [11-08], [11-07]). In this sense, the efforts made by the EU (within the DCF program covering at least 10% of fishing trips) and ICCAT carrying out observer programs promote better monitoring of bycatch. However it would be important that all fleets operating in the Atlantic implement observer programs to have better bycatch estimates. In the EPO the IATTC has an observer program with 100% of coverage which allow monitoring the bycatch. However, the same analysis was not carry out with the Mexican fleet because Mexican purse seiners mainly fish on dolphin-associated tuna schools, and the dolphin bycatch has been reduced since the implementation of the La Jolla agreement in 1992. Besides monitoring the bycatch, it is important investigate the role in the epipelagic ecosystem of the main species caught incidentally and the possible consequences of declining their populations. In this sense, integration of the fishermen behavior to reduce bycatch is equally important in order to (1) avoid high bycatch rates making decisions before setting, and (2) what to do with the bycatch once on board, as well as the involvement of fishing technologists is important. Moreover, the growing demand of some bycatch species in the local market of Abidjan results relevant in the purse seine fishery management. Fishermen will remain encouraged to not avoid or reduce bycatch, as long as the existence of a commercial value and an unregulated market to these species. In this sense, the proposal of some authors (e.g. Zhou 2008; Garcia et al. 2012) about “balance harvesting” results interesting in such a context like in Abidjan and may be integrated by the ICCAT. However it remains difficult assessing how much could be caught of each species group.

The statistical tools used in this dissertation permitted to investigate the fleet dynamics in some facets. However, other statistical tools may be utilized to analyze fishing behavior, for instance the artificial neuronal networks for simulation have been applied in terms of decisions to allocate fishing effort (Dreyfus-León 1999) as well as sharing information among fishermen (Gaertner and Dreyfus-León 2004). More recently with the implementation of vessel monitoring systems (VMS) allow knowing accurate the time and position of fishing vessels, and it is possible to estimate speed and direction. This data has been utilized to analyze tuna purse seiners in the western Indian Ocean (Walker 2010; Bez et al. 2011). Moreover VMS data have been analyzed using artificial neural networks to identified set positions (Bertrand et al. 2008; Joo et al. 2011). Notwithstanding, this dissertation is one step toward the integration of fleet dynamics to improve tuna purse seine fishery management.

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Annex T1

T1 Environmental conditions in the eastern tropical Atlantic and Pacific Oceans

Regional ocean processes (e.g. temperature, oxygen, salinity, stratification and circulation) greatly influence marine organisms. In the case of tropical tunas these processes widely determine the abundance as well as their migrations and the possibilities for fishermen to capture them. Therefore it is important to describe the oceanic environment of the study areas, especially because seasonal and interannual variations of the climate largely define the oceanic environment.

The regions that will be described in this chapter correspond to the eastern tropical Atlantic and the eastern tropical Pacific oceans, where the French and Mexican tropical tuna purse seine fleets operate respectively. These Oceans share many common climatological features such as easterly trade winds, eastward shoaling thermocline, an eastern cold tongue and a northerly Inter-Tropical Convergence Zone (1TCZ). However, a comparison of climate variability between the two oceans reveals differences (Xie et al. 1999). The Pacific is dominated by the equatorially symmetric El Niño-Southern Oscillation (ENSO) while the Atlantic ITCZ is controlled by changes in inter-hemispheric sea surface temperature (SST) gradient (Xie et al. 1999). As a consequence, Pacific Ocean is characterized by a large yearly variability and a low seasonal variability while this is the opposite for the Atlantic.

T2 Oceanic circulation

In the Atlantic Ocean, the asymmetry of the Azores and of the Saint Helena anticyclones is reflected in the superficial oceanic circulation (Gouriu 1993). The seasonal changes of the wind field lead to variations of the circulation in the tropical Atlantic (Stramma and Schott 1999).

In the eastern Atlantic, the Canary Current runs along the Moroccan and Mauritanian Coast, and leaves southwestward the coast around 20° N latitude (Binet and Marchal 1993). In the southern hemisphere, the Benguela Current extends northward along the Namibia coast, shifting westward around 17°S latitude.

The tropical Atlantic surface circulation is bounded by the equatorial edges of the northern and southern subtropical gyres (**Figure T1**). This includes the westward North Equatorial Current (NEC) and South Equatorial Current (SEC). The NEC is a westward flow which is broad and uniform (Gouriou 1993). The North Equatorial Counter Current (NECC) is an eastward flow between 4°N latitude and 8°N latitude. The NECC presents prominent seasonal variations in the western region. East of 20°W longitude, the NECC is permanent. The eastward extension of the NECC is the Guinea Current which is a shallow surface flow. The Guinea Current extends along the African coast (5°N-2°N) to the end of the Bay of Biafra. The position of the Guinea Current remains fairly constant (Binet and Marchal 1993). It is reinforced however by the monsoon and can be modified by the Harmattan wind (Hardman-Mountford and McGlade 2003).

The other important surface flow in the Gulf of Guinea is the SEC, which a westward flow (Stramma and Schott 1999). At the equator, the thickness of the SEC sharply decreases due to the presence of the Equatorial Undercurrent (EUC). The SEC is divided in three branches: (1) the northern SEC (nSEC), (2) the central SEC (cSEC) and (3) the southern SEC (sSEC). The sSEC is a broad and slow flow between 10°S and 25°S east of 30°W (**Figure T1**).

In the intertropical Atlantic there is a system of three subsurface counter currents flowing eastward (Gouriou 1993). The best known is the EUC which is strongest in the west and is weakening along its path as a result of frictional losses to the surrounding waters (Binet and Marchal 1993). The EUC has a width of around 200 km and a thickness of 150 m (Gouriou 1993). The eastward flow of the EUC is against the dominant winds, producing an east-west slope of the thermocline (Stramma and Schott 1999).

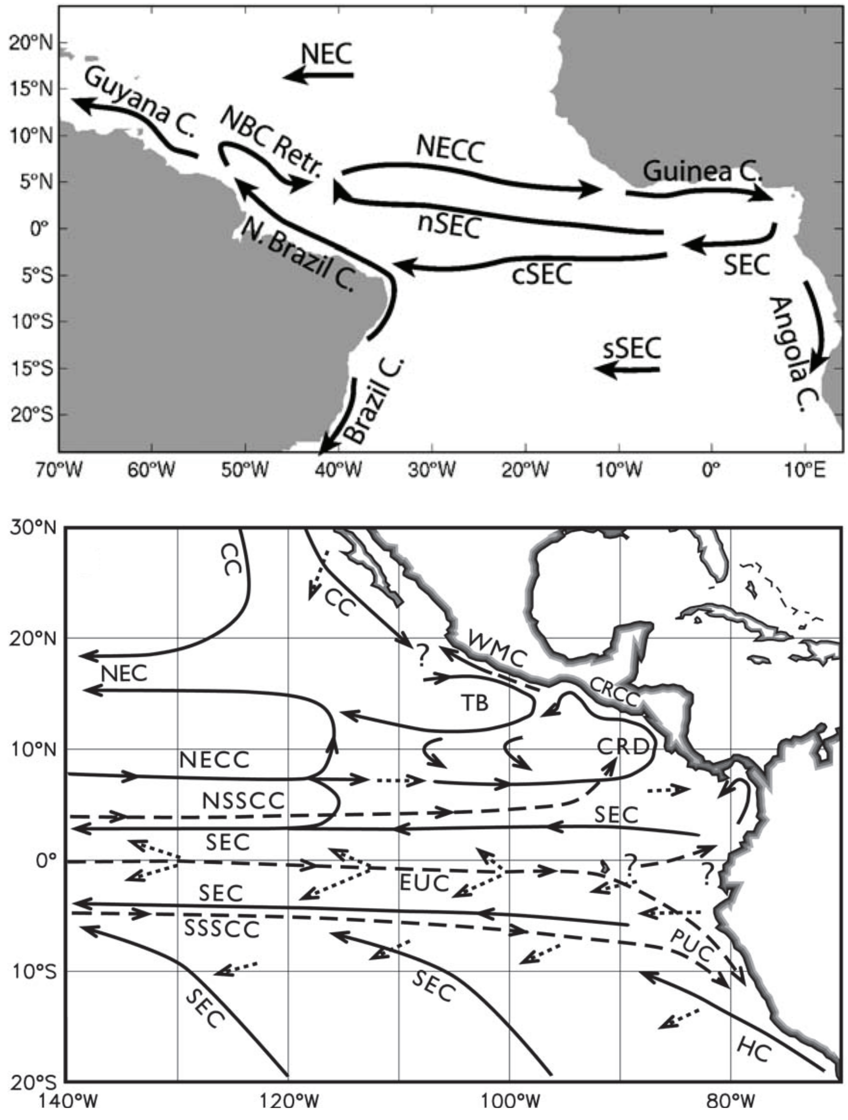


Figure T1 Schematic circulation in the tropical Atlantic Ocean (upper; Source: Lumpking and Garzoli 2005) and in the tropical Pacific Ocean (bottom; Source: Kessler 2006)

In the eastern Pacific Ocean (EPO), the major westward components of the equatorial current system are the NEC and the SEC (**Figure T1**). The California Current flows southward along the coast of Baja California and turns west, feeding the NEC predominantly in boreal spring (Kessler 2006). The NEC and the SEC are directly wind-driven. They reach their greatest strength during the winter of their respective hemispheres when the trades are strongest (Tomczak and Godfrey 2003).

The EUC is the most prominent of all eastward flows. This current extends rapidly over a distance of more than 14 000 km along the equator with a thickness of only 200 m and a width of at most 400 km (Tomczak and Godfrey 2003). The eastward flow of the NECC, in the equatorial current system, varies seasonally in strength and position (Kessler 2006). In boreal spring, there is no eastward flow at all along 110° W longitude anywhere south of the California Current. In boreal fall and winter the NECC appears to flow all the way to the coast. At 110° W longitude the structures of the EUC and SEC are similar to that observed at 125° W longitude (Kessler 2006).

The wind forcing associated with the ITCZ between the two subtropical highs produces the long ridges (high atmospheric pressure) and troughs (low atmospheric pressure), bounding the zonal currents of the central Pacific (Fiedler and Talley 2006). A striking bowl (Tehuantepec Bowl) and dome (Costa Rica dome) are evidenced at 13°N, 105°W and 9°N, 90°W, respectively. These features appear to be the eastern ends of the thermocline trough and ridge that define the limits of the NEC across the basin (Kessler 1990). The Tehuantepec Bowl is a shallow feature that is barely visible in the 100 m dynamic height (Kessler 2006).

The Costa Rica Coastal Current (CRCC) is a northwestward flow on the east side of the Costa Rica Dome. The CRCC continues along the coast into the Gulf of Tehuantepec, where it turns south to flow around the south side of the Tehuantepec Bowl (**Figure T1**). This northward extension is seasonally modulated as the Costa Rica dome expands and contracts (Kessler 2006). The CRCC extends quite deeply into the water column, with an appreciable flow below the thermocline. The anticyclonic flow around the Tehuantepec Bowl produces a strongly southeastward current along the coast of Oaxaca into the Gulf of Tehuantepec that cuts off the CRCC and forces it to turn offshore (Kessler 2006).

T3 Sea surface salinity and temperature

In tropical areas, the spatial distribution and temporal variability offshore of the Sea Surface Salinity (SSS) are caused by the evaporation-precipitation balance, advection and mixing. In the coastal areas, the river runoff drastically changes the SSS.

In the tropical Atlantic Ocean (**Figure T2**), minimum SSS occurs in September-October centered at 8°N latitude, from the African coast to 40-45°W longitude and west of 65°W near 20°N. The local evaporation-precipitation balance is the main cause of the variability observed (Dessier and Donguy 1994). Guinean waters are masses of warm low salinity water resulting from the high precipitation and numerous rivers in the eastern Gulf of Guinea (Hardman-Mountford and McGlade 2003). Low salinity patches are found in the middle of the Atlantic, particularly in fall. These patches may consist of lenses of Amazon waters advected eastward by the NECC (Dessier and Donguy 1994). In the tropical Atlantic interior there is a maximum SSS variability that migrates from a southern position near the equator in May-March to a northern position in September-November close to 10° N latitude (Dessier and Donguy 1994; Reverdin et al. 2007).

The SST in the Gulf of Guinea varies between 27°C and 29°C outside of the upwelling seasons (Allersma and Tilmans 1993), but can drop to below 22°C at the coast during the major upwelling (Binet and Marchal 1993). Stratification becomes enhanced during the warm seasons, especially the long warm season. The depth of the tropical thermocline can vary seasonally between 10 and 60 m in the Gulf of Guinea (Hardman-Mountford and McGlade 2003). The largest seasonal fluctuations of the SST in the tropical Atlantic Ocean occur in the Gulf of Guinea, where the thermocline is shallow. The most characteristic feature is the appearance of a cold tongue east of 20°W longitude in September, along and south of the equator and then expands westward (Carton and Zhou 1997). In the north the SST reaches its peak in September, while the south peak is in March-April. Between April and August temperatures at the equator drop less than 23°C (Hardman-Mountford and McGlade 2003).

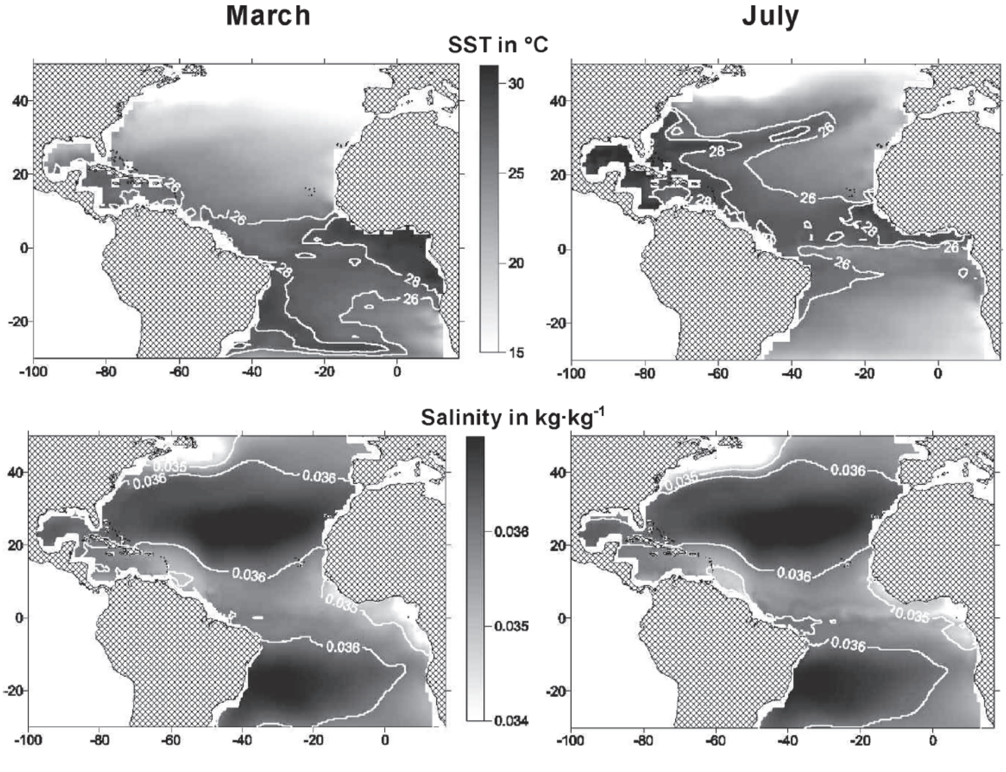


Figure T2 Sea surface temperature (upper) and sea surface salinity (bottom) in the tropical Atlantic Ocean. Source: Maury et al. 2001.

In the EPO the most characteristic surface feature is the eastern Pacific warm pool (SST above 27.5° C, **Figure T3**), with low salinity (i.e., tropical surface water over a shallow and strong pycnocline). The equatorial cold tongue is centered directly on the equator west of 120° W longitude. Temperature of the cold tongue decreases towards the east as progressively cooler waters are upwelled from the EUC (Kessler 2006). The Equatorial Surface Water has moderate salinity and is over a shallow but relatively weak pycnocline (Tsuchiya and Talley 1998). In this region seasonal and ENSO variability are relatively low (Fiedler and Talley 2006). Cool low salinity eastern boundary current waters flow into the eastern tropical Pacific from the north and south (Fiedler and Talley 2006).

Warm subtropical surface waters with high salinity flow into the eastern tropical Pacific as Subtropical Underwater after being subducted into the thermocline (O’Connor et al. 2002). The pycnocline in the EPO is a thermocline reinforced by a halocline and is shallow and strong (Fiedler and Talley 2006). In the average, the lowest SSS is observed in the coastal waters of Central America and Baja California, and it extends along the 10°N latitude (**Figure T3**). Along the equator, coastal Peru, Baja California and at the Costa Rica Dome, the upwelling is evidenced (Fiedler and Talley 2006). The water in thermocline is upwelled and mixed into the surface layer by winter wind jets at the Gulfs of Tehuantepec, Papagayo, and Panama. The main processes which control EPO thermocline depth are (1) the currents export water and accumulated heat from the eastern to the western tropical Pacific, consequently the thermocline is much shallower in the east; (2) the currents interact with the rotation of the Earth to lift the thermocline at the gyre edges and depress it in the gyre centers, shoaling the thermocline over substantial portions of the EPO, and in some areas (3) local winds drive additional thermocline shoaling via wind-driven upwelling (Pennington et al. 2006). The first two of these processes operate on basin-scales while the third is locally-driven, but all three vary spatially within the EPO (Pennington et al. 2006).

The eastern Pacific warm pool is part of the western Hemisphere warm pool (WHWP), being influenced by ENSO which superimposes on the seasonal variability (Wang and Fiedler 2006). The development of the warm pool begins during the boreal spring in the eastern north Pacific, then reaches the EPO in May, but shrinks and spreads along the coast. This is an important region of warm waters which, in conjunction with strengthening of the ITCZ, triggers the beginning of the summer monsoons. During the transition period in June the warm pool decays in the EPO (Wang and Fiedler 2006). During boreal winter there is no water warmer than 28.5° C in this part of the Pacific.

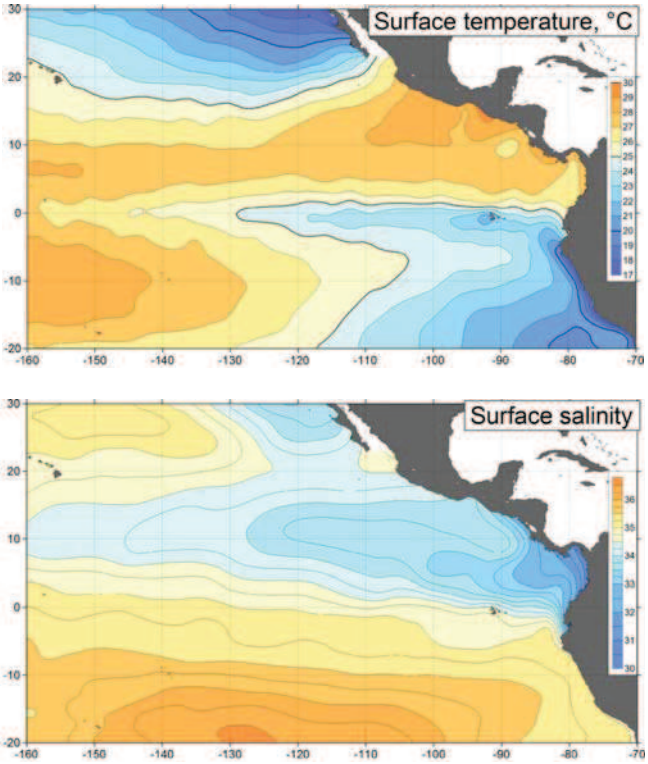


Figure T3 Sea surface temperature (upper) and sea surface salinity (bottom) in the eastern tropical Pacific Ocean. Source: Fiedler and Talley 2006.

T4 Upwelling and primary production

The eastern tropical Atlantic accounts for 12% of Atlantic Ocean primary production (Longhurst 1995). The main upwellings are localized close to the Canary Current, the Benguela Current, the equator, and in the coasts of Côte d'Ivoire and Ghana (**Figure T4**). The Canary Current upwelling is characterized by a strong seasonal variability and a large contrast between the waters in the north and south (Chavez and Messié 2009). The Canary Current upwelling reaches its southernmost extent in winter when the trades are strongest, extending until Senegal. During summer the upwelling is restricted to north Cap Blanc (21°N latitude). Between 10°N latitude and 20°N latitude upwelling becomes semi-continuous with a spring maximum (Chavez and Messié 2009) and a corresponding maximum of chlorophyll *a* (Chl *a*).

The Benguela Current upwelling is strongest in the south during boreal fall and winter when the trades are steady. During boreal summer it extends northward but becomes more intermittent because the trades are interrupted (Tomczak and Godfrey 2003). The Chl *a* primary production from the upwelling reaches 18° S latitude from July to January (Figure 1.4).

From June to September the equatorial upwelling, injects nutrients into the upper mixed layer leading to surface Chl *a* (**Figure T4**) and primary production maxima. This upwelling is weak from October to May (low Chl *a*). Nutrient-depleted upper mixed layer is separated by a strong thermocline from the nutrient-rich, lower layer (Herbland and Le Bouteiller 1982).

The upwelling along the coasts of Côte d'Ivoire and Ghana occurs from July to September, driving the biology of the system in the Gulf of Guinea (Binet and Marchal 1993). It should be noted that the winds in this region are not appropriate for an upwelling because they are always very soft (Hardman-Mountford and McGlade 2003). This upwelling is caused by Kelvin waves generated off the coast of Brazil and then reach the Gulf of Guinea about one month later, showing strong regular upwelling events (Tomczak and Godfrey 2003).

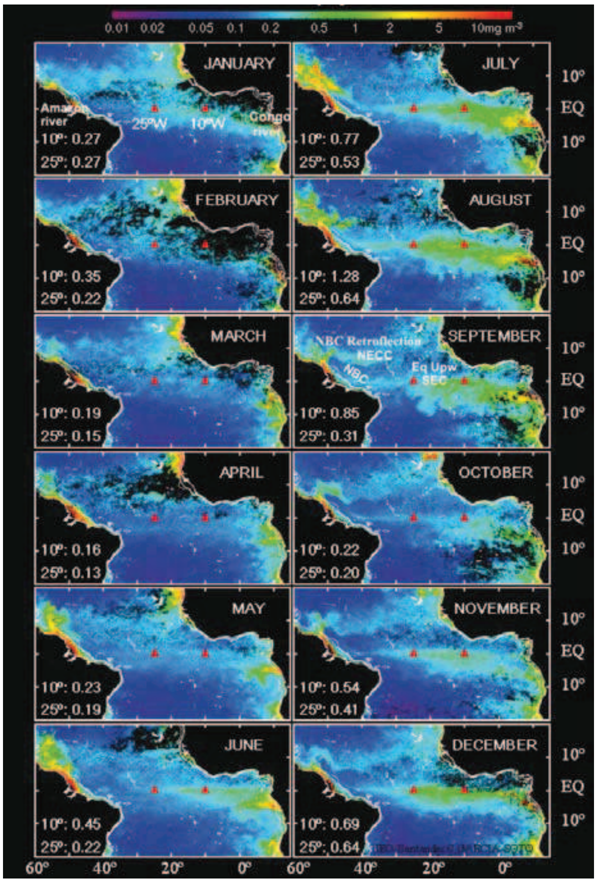


Figure T4 Monthly chlorophyll *a* concentration from SeaWiFS in the tropical Atlantic for 2001. Source: Pérez et al. 2005

The EPO accounts for 23% of Pacific Ocean primary production (Pennington et al. 2006), that is to say approximately twice that observed for the eastern Atlantic. In this Pacific region, the main upwellings are located in the California Current, the Peru Current, the equator, and along the eastern Pacific warm pool (**Figure T5**).

In the California Current system the winds along the coast are much more seasonal than along the coast of Peru. During October-March, poleward flow at the surface is observed over the shelf and even further offshore, reaching its peak in January-February. Coastal upwelling with equatorward surface flow prevails during spring and summer (Tomczak and Godfrey 2003). In the west of the Baja California peninsula, the upwelling is throughout year but weak (Chavez and Messié 2009).

The coastal upwelling in Peru Current system is the most impressive coastal upwelling system of the world (Tomczak and Godfrey 2003). It extends from Southern Chile (~45°S) to northern Peru (~4°S), where cool-upwelled waters collide with warm tropical waters forming the Equatorial Front. The Peruvian upwelling includes three defined biomes: (1) a highly productive seasonal upwelling system off southern Chile (30-40°S); (2) a large, moderate to low productivity "upwelling shadow" off northern Chile and southern Peru (18-26°S); and (3) the highly productive year-round Peru upwelling (4-16°S).

The equatorial upwelling is created by the reversal of Coriolis acceleration to either side of the equator. This upwelling is centered on the equator but is strongest in the central Pacific where the trade winds are most easterly. The equatorial cold tongue is known for fertilizing the euphotic zone with macronutrients. Phytoplankton biomass is generally maximal on or near the equator. Biomass is enhanced south of the equator in the far EPO (<95°W).

The eastern Pacific warm pool is not penetrated by the subtropical gyre circulation (Amador et al. 2006). This warm pool is clearly evidenced in satellite Chl *a* images as areas of enhanced biological production (Pennington et al. 2006). This results from nutrient supply by wind-driven upwelling and near-surface mixing. During boreal winter strong, but intermittent, wind blows across Central America from the Gulf of Mexico and the Caribbean into each of the three Gulf regions (Amador et al. 2006; Willett et al. 2006). Upon reaching the Pacific, this offshore-directed wind jets fan out (Pennington et al. op. cit.). Such velocity gradients produce frictional gradients on the sea surface termed as 'wind stress curl' (Kessler 2006). When surface currents diverge the pumping is upward and the thermocline shoals. Biological productivity is coupled to the wind forcing with areas of high Chl *a* associated with mixing, upwelling, and eddy transport (Willett et al. 2006).

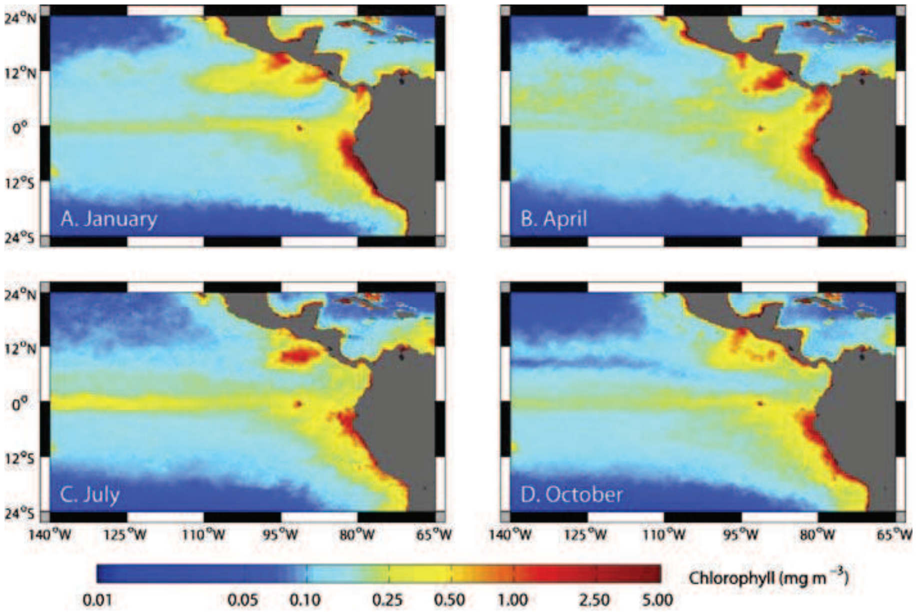


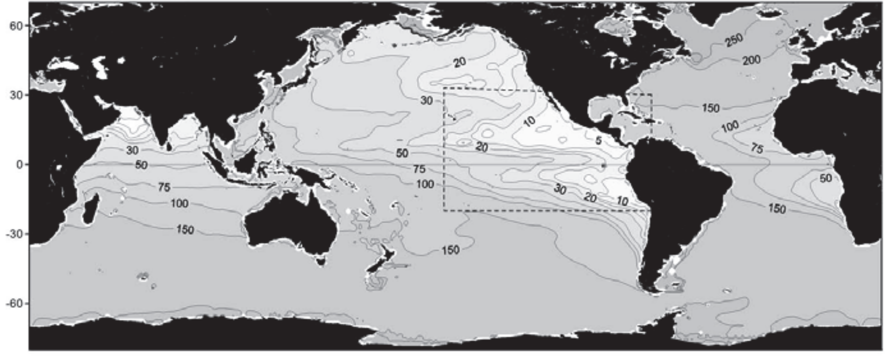
Figure T5 Chlorophyll *a* concentration from SeaWiFS data (1997-2005) in the tropical Pacific. January (A), April (B), July (C) and October (D) emphasize seasonal differences. Source: Pennington et al. 2006

T5 Oxygen minimum zones

The air-sea exchanges allow ventilation of the ocean's interior. These exchanges establish water mass conditions and supply oxygen to the surface mixed layer. Volumes of the interior ocean that are relatively poor in oxygen are called oxygen minimum zones (OMZs). These OMZs are important because form a sharp barrier for living organisms intolerant to hypoxia (e.g., tuna species).

In the eastern tropical Atlantic there are two core of oxygen minimum located in the Guinea dome and in the Angola dome respectively (**Figure T6**). They comprise the Central Water and the Antarctic Intermediate Water layers (Stramma et al. 2005). The poleward extent of the OMZ in the eastern South Atlantic is similar to the extent in the North Atlantic. The southern limit of the OMZ is the Benguela Current transporting oxygen rich water northwestward into the tropical South Atlantic. The oxygen supply to the OMZs is mainly from the west with near-equatorial currents (Karstensen et al. 2008). The surface concentration increases progressively toward the south as a result of the cooling of waters which increases the solubility of oxygen. At the equator the oxycline approaches the surface and the oxygen content shows a minimum. At the equator the equatorial current transports waters rich in oxygen. A second maximum is associated with the southern subsurface countercurrent near 4-5°S latitude. On both sides these maxima appear among the oxygen depleted zones from Côte d'Ivoire to near 12°S latitude (Gouriou 1993).

(a) min[O_2], µmol/kg



(b) Depth of min[O_2], m

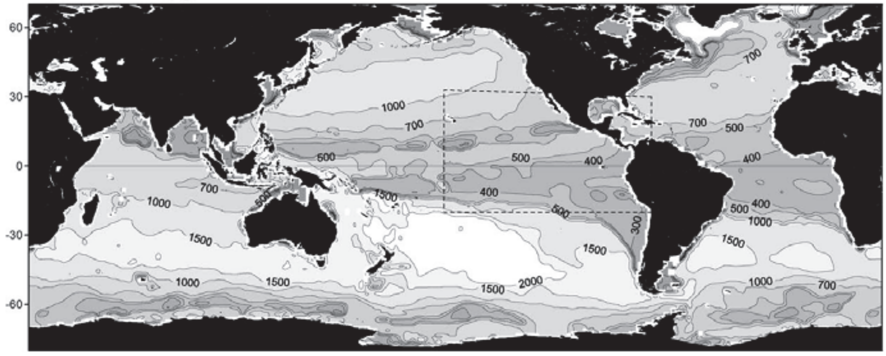


Figure T6 Global oxygen minimum layer, (a) minimum dissolved oxygen concentration (µmol kg^{-1}), and (b) depth of minimum oxygen concentration. Source: Fiedler and Talley 2006.

The EPO waters beneath the pycnocline are very low in oxygen (Fiedler and Talley 2006). However, the EPO's OMZ is located in the Costa Rica dome between the pycnocline and intermediate waters (Figure T6). This OMZ is remarkable for its size and degree of hypoxia (Kamykowski and Zentara 1990). Instead of flowing directly into the EPO, they turn westward to feed the NEC (Karstensen et al. 2008). There is some enhancement of oxygen in the far west by lateral mixing with waters from the South Pacific. As a result the NECC supplies water of relatively high oxygen concentrations towards the eastern basin (Fiedler and Talley 2006). The extreme oxygen deficiency in the EPO's OMZ is attributable to several factors: (1) high phytoplankton production at the surface; (2) a sharp permanent pycnocline that prevents local ventilation of subsurface waters; (3) a slow and convoluted deep circulation and therefore old “age” of waters beneath the pycnocline (Fiedler and Talley 2006). Oxygen minimum concentrations are low north of the equator because there is no source of oxygen-saturated, high-density water at the surface in the North Pacific (Reid 1973). There are no direct interior pathways from subtropical ventilation regions towards the equator in the North or South Pacific at these subpycnocline depths. The oxygenated water subducted from the surface must come from the west in the subsurface countercurrents (Johnson and McPhaden 1999). Oxygen concentrations are high in the oxygen minimum along the equator due to the more rapid transport of oxygenated water from the western Pacific in the EUC (Tsuchiya et al. 1989).

Publications :

Torres-Irineo E., Gaertner D., Chassot E., Dreyfus-León M. *In Prep*. Effects of the introduction of technology on board on the purse seine fleet dynamics in the tropical eastern Atlantic.

Publications dans des revues avec arbitrage :

Torres-Irineo E., Gaertner D., Delgado de Molina A., Ariz J. 2011. Effects of time-area closure on tropical tuna purse-seine fleet dynamics through some fishery indicators. Aquatic Living Resources. DOI:10.1051/alr/2011143.

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Torres-Irineo E., Gaertner D., Delgado de Molina A., and Ariz J. (2010). Effects of time-area closure on tropical tuna purse-seine fleet dynamics through some fishery indicators. International Commission for the Conservation of Atlantic Tunas (ICCAT). Madrid, Spain, Octobre 8.

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Aquat. Living Resour. 24, 337–350 (2011)

DOI: 10.1051/alr/2011143
www.alr-journal.org

Effects of time-area closure on tropical tuna purse-seine fleet dynamics through some fishery indicators

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Received 27 February 2011; Accepted 29 August 2011

Abstract – Time-area closures have become a frequently used tool to control fishing effort and protect feeding and spawning areas. However, because time-area closure strata are mainly based on biological and ecological considerations, and do not accounts for fishermen's behavior-at-sea, this type of regulation tool may not entirely achieve its objectives. With the aim of comparing the impact of two different time-area regulations: (1) a moratorium on Fish Aggregating Devices (FAD) sets (1997–2005) and (2) a no-take area for surface fleets (2005–2010) on the dynamics of the European (EU) tuna purse seine fleet operating in the eastern tropical Atlantic, several fishery indicators were evaluated through a Before-After, Control-Impact (BACI) approach. The results showed that prior to any regulation, the fleet used to be concentrated within the Gulf of Guinea area. During the first years of the moratorium on FAD (from November to January within a large region in the eastern Atlantic) there was a movement towards outside the protected area, increasing the total sets on FAD (restricted fishing activity). In general, this moratorium fulfilled its objectives; however, it was not respected during the last years of this regulation. The no-take time-area closure restricted all tuna catches for the surface fisheries but only in November and within a small area (i.e., the Picolo zone). As a result, there was an increase in activities on free schools outside the no-take area. Our findings suggest the use of some simple fishery indicators to understand fleet dynamics as a complement of ecological information before implementing new time area closures. Furthermore, since tunas are highly mobile species, anticipating the possible re-allocation of effort of purse seiners to adjacent areas in response to the spatial regulation is required to design different candidate time-area closures and to evaluate their effectiveness to protect juvenile tunas.

Key words: Time-area closure / Fleet dynamics / Tropical tuna / Fishery indicators

1 Introduction

Seasonal area closure has been used by managers to protect harvested species in mature fisheries (Branch et al. 2006; Agardy et al. 2011). However, this management tool is more likely to be useful when species are of low mobility or sessile, while for highly mobile species such tool may have little effectiveness in protecting them (Hilborn et al. 2004; Harley and Suter 2007; Jensen et al. 2010). For highly mobile species, it was suggested from simulation studies that to obtain some benefits, a very large closure area (as large as 85% of the total area of the stock) may be required (Le Quesne and Codling 2008).

This case study concerns the tropical tuna surface fishery (purse seiners and baitboats) which is a multispecies fishery on yellowfin (*Thunnus albacores*), skipjack (*Katsuwonus pelamis*) and bigeye tuna (*T. obesus*). Tuna schools are detected visually at the surface of the sea and the main fishing modes depicting purse seine operations are non-associated school sets (mainly dominated by large yellowfin) and natural, or artificial, drifting floating object sets (in this case the catch is composed by juvenile yellowfin and bigeye and by juvenile and adult skipjack).

1.1 Spatial regulations in the eastern tropical Atlantic Ocean

In 1996, by means of recommendation [96-01], the International Commission for the Conservation of Atlantic Tunas (ICCAT) was aware of the large increase in the catches of bigeye tuna and juveniles observed since the beginning of the

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Table 1. Main characteristics of the two management measures adopted by ICCAT for tropical tunas.

	Moratorium on FAD	Time-area closure
Years	1997–2005	2005–2010
Months	November-January	November
Area	4° S-5° N and 20° W and the African coast	5° N and Equator 0° and 10° W to 20° W (Picolo Zone)
Restrictions	Fishing on FAD	All surface fishing gears

1990s in the Atlantic Ocean. Hence, within the framework of the Bigeye Tuna Year Program (BETYP), ICCAT requested that further analysis must be carried out on these issues to determine protected fishing areas and seasons through observer programs for all type of fleets. In the case of the EU purse seine fleets (mainly Spain and France), different assumptions were considered to explain the increase in juvenile catches. Among others, it was a change in catchability due to the extension of the use of artificial floating objects (or Fish Aggregating Devices, hereafter named FAD), in new areas in the eastern Atlantic Ocean (Ariz and Gaertner 1999).

In such a context, the purse seine fishery has been the subject of several regulatory measures. In 1997, the French and Spanish tuna boat owner companies implemented a voluntary protection plan for juvenile tunas, which consisted of a ban on FAD fishing operations during a three-month period over a large portion of the Gulf of Guinea. This moratorium was adopted and extended to all surface fleets by ICCAT in 1999. As there were few changes since the voluntary moratorium, the entire period of 1997–2005 is named hereafter as moratorium on FAD.

In 2004, ICCAT adopted recommendation [04-01] “Multi-year conservation and management program for bigeye tuna”, with the goal of conserving and managing bigeye tuna stocks and because of the concern about the increase in illegal, unreported and unregulated (IUU) fishing activities. This recommendation entered into force in June 2005, and consisted in resizing the area limits of the former recommendations and reducing the months’ period (Table 1). Unlike recommendations [98-01] and [99-01], which banned the use of FAD, recommendation [04-01] prohibited tuna catches in the restricted stratum for all surface fishing gears, which is named hereafter as closure or no-take area.

Different studies have evaluated the effects of these spatial regulations, mainly on the catches (Diouf et al. 1999; Goujon and Labaisse-Bodilis 2000; Ariz et al. 2001; Goujon 2004a; Goujon 2004b; Ariz et al. 2005; Cass-Calay et al. 2006; Brooks and Mosqueira 2006; Ariz et al. 2009; De Bruyn and Murua 2010). However, there is no document that has evaluated the consequences of the establishment of a spatial regulation on purse seine fleet behavior at sea. Even if the idea of implementing a spatial regulation is to protect the harvest species, it will affect the users in some way, and thus it is necessary take into account the fleet response to improve the fishery management (Johannes et al. 2000; Wilen et al. 2002; Salas and Gaertner 2004; Kaiser 2005; Branch et al. 2006; Poos and Rijnsdorp 2007). For this reason, the aim of this paper was to evaluate the effects of two types of spatial regulations on the purse seine fleet behavior using different fishery indicators.

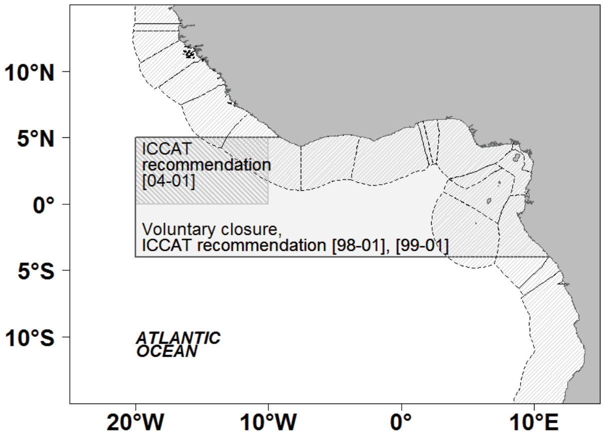

Fig. 1. Zones of the different spatial regulations: (1) the voluntary moratorium and ICCAT recommendations [98-01] and [99-01] on Fishing Aggregating Devices (FAD) were instituted during the period 1997–2005 from November to January of the following year (gray rectangle); (2) the no-take regulation in November that replaced the moratorium on FAD was in the Picolo zone from 2006 up to the present (small shaded rectangle). The shaded contour represents the economic zones (200 nautical miles).

2 Materials and methods

2.1 Data

The analysis was based on logbook data reported by EU purse seiners (France, Spain, and associated flags) before the multispecies correction procedure made on a routine-basis with samples taken on landing sites. Consequently, some misidentification between species may occur. It was decided, however, to work with these declarative data because they are more representative in terms of size category of the fish in a specific set than corrected data on the fishing modes (i.e., in contrast to the corrected data which reflect the sampling species composition over a large strata, the declarative data better reflect the size categories of tunas caught during a specific set, associated with a specific fishing mode and specific spatial coordinates).

For the moratorium on FAD period an increment is expected in the activities on free schools both inside and outside the moratorium on FAD area (Fig. 1), whereas for FAD activities there should be an increment outside moratorium area. On the other hand, the fishing activities (except those on free school) are expected to decrease inside the area (e.g., days with catch) once the moratorium enters into force. Regarding the no-take recommendation [04-01], a total reallocation of surface fishing effort is expected and, as a consequence, a rise in fishing activities outside the area during the month of November on both free schools and FAD as well as the corresponding catches. A summary of the characteristics of each regulation is presented in Table 1.

2.2 Fishery indicators

To analyze the activity of the purse seine fleet and to estimate whether the fleet dynamics changed as a consequence of the two management measures, different indicators were used on a monthly basis (Table 2). These indicators were averaged for the vessels operating in a given month. Such indicators were: the total number of fishing days (Dy^+); the number of $1^\circ \times 1^\circ$ squares explored successfully (Sq^+) which represent the success of the fleet in terms of catch independently of the fishing method used; the fishing time (FT) which represents the time spent by the fleet in the zone; the number of sets on free schools ($FrSc$), used to detect whether there was an increase in the effort associated with this method due to the interdiction on FAD; the number of sets on FAD (FAD), assumed to represent directly the effects of the regulation measures (as mentioned previously the aim of the regulation on FAD was to reduce the catch of juveniles). In addition, these last two indicators were considering positive sets and unsuccessful sets (i.e., without catch). Catch with FAD ($FadC^+$), catch of juveniles with FAD ($JuvC^+$) and catch of large yellowfin tuna on free schools (YFT^+) are representative of the fishing modes selected by fishermen.

Fishery indicators were performed for the two periods considered (1995–2005 and 2000–2008). With the aim of pointing out a contrast between before and after the corresponding spatial regulation, the first period was divided from 1995 to 1997 (before) and from 1997 to 2005 (after) and the second period was from 2000 to 2004 (before) and from 2005 to 2008 (after). Not all the vessels operated in both periods of time. Consequently, to ensure that the results represent the effects of each regulation, only vessels with at least 50% of presence in each period were considered. This supposes that these vessels would have more knowledge about spatial and temporal strata. Furthermore, some vessels operated only before or after each regulation, and in this case the information supplied by them did not take into account the effects of the regulations. Thus, the indicators were calculated on the basis on information provided by 33 and 25 vessels for the first and the second period, respectively.

2.3 Statistical analysis

Impact assessment aims to evaluate (i) whether or not a stress has changed the environment; (ii) to determine which components are adversely affected; and (iii) to estimate the magnitude of the effects. Theoretically, when information is available prior to the potential impact, the design is often referred to as a Before-After Control-Impact (BACI) design (Smith 2002). In addition, when historical data are available it is possible to estimate the effects of an impact, and if it is possible to have a control zone it will improve the estimation of such an impact (Eberhardt and Thomas 1991; Wiens and Keith 1995).

Since the moratorium region might suffer changes outside as well as inside for many reasons (e.g., changes in fishing effort over the years, large-scale environmental conditions, etc.) it was difficult to define a control zone. Consequently, the assessment of the effects on purse seine fleet dynamics was conducted by a Before-After design (see Appendix 1 for an overview of BACI analysis). This is the simplest approach, which involves data prior to the activity and compares them with data after the activity. The typical approach to analysis is to treat the data as independent samples (Eberhardt and Thomas 1991; Wiens and Keith 1995; Smith 2002).

The analysis[1] was carried out using ANOVA when the indicator data satisfy the assumptions of normality and homoscedasticity, or a Kruskal-Wallis test when assumptions were violated.

The data were divided inside and outside depending on the regulation measure and coded to differentiate the before and after period, permitting taking replicated samples at repeated times, because each year the impacted area was sampled by the vessels. The inside-outside interaction was difficult to interpret and to evaluate; thus, to determine if there was an effect outside of the area the same analysis with the corresponding data was carried out.

Notice that before the entry into force of the no-take regulation there was already an effect from the moratorium on FAD. To attempt to mitigate this effect, the period before closure was considered from 2000, because from this year all fleets had to comply with the moratorium on FAD and thus it was assumed that normal conditions were the moratorium.

In addition to the BACI approach, descriptive analyses were done to show the spatial distribution of the number of sets in both fishing methods (free schools and FAD) and before-after of the spatial regulations. To do this, an estimate was made of the average of the number of sets of each fishing method by each time a cell ($1^\circ \times 1^\circ$) was visited. The maps were carried out by using R package PBSmapping[2].

3 Results

3.1 Moratorium on fish aggregating devices

3.1.1 Before EU voluntary protection plan

Before the implementation of the moratorium on FAD (1995–1997) for the three-month period (November–January), each EU vessel carried out, on average, more fishing activities within the area than outside the moratorium area (Fig. 2). Only activities related with free schools had similar values throughout the time series. It must be stressed that within the protected area in November and December there were more sets on

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[1] The analysis was conducted by using R version 2.11.1 URL http://www.R-project.org/

[2] PBSmapping: Mapping Fisheries Data and Spatial Analysis Tools. R package version 2.61.9, http://CRAN.R-project.org/package=PBSmapping

Table 2. Fishery indicators average Before-After each spatial regulation (moratorium on FAD and Picolo no-take area) and inside and outside each zone. Main statistics from Before-After analysis inside and outside of each spatial regulation (notice that fishing activities inside Picolo no-take area were banned). When the indicators were normal and homoskedastic (the variance of the errors over the sample are similar), an ANOVA was applied; the otherwise Kruskall-Wallis rank sum test was applied.

Moratorium on FAD					
		Inside		**Outside**	
Indicator	Description	Before	After	Before	After
Dy^+	Days with catch	10.2	5.8	4.7	5.1
Sq^+	Square visited with catches	7.3	4.4	3.5	4.1
FT	Fishing time (h)	282.3	251.8	145.9	160.7
FrSc	Number of free school sets	7.7	7.9	3.5	1.9
FAD	Number of FAD sets	8.6	2.1	3.6	6.1
$FadC^+$	FAD catch (t)	227.0	93.5	85.5	134.0
$JuvC^+$	Juveniles < 1.8 kg catch (t)	57.8	6.7	26.8	9.8
YFT^+	YFT catch on Free school (t)	99.9	91.0	114.2	30.6

Inside Moratorium on FAD								
ANOVA					Kruskall-Wallis			
Indicator	Sum Sq	*df*	*F*	Pr(>*F*)	Indicator	λ^2	*df*	*p*-valu
Dy^+	104.4	1	29.071	8.54 × 10−6	*FT*	4.127	1	0.042
Sq^+	48.2	1	30.434	6.04 × 10−6	*FrSc*	0.056	1	0.813
$JuvC^+$		1	24.345	3.05 × 10−5	*FAD*	13.580	1	0.0002
					$FadC^+$	9.431	1	0.002
					YFT^+	0.056	1	0.813
Outside Moratorium on FAD								
Dy^+	0.60	1	0.132	0.720	*FrSc*	2.645	1	0.104
Sq^+	1.49	1	0.542	0.470	$JuvC^+$	1.182	1	0.277
FT	725.3	1	0.691	0.415	YFT^+	4.880	1	0.027
FAD	19.8	1	4.418	0.048				
$FadC^+$	7793	1	0.776	0.389				

No-take area			
	Inside	**Outside**	
Indicator	Before	Before	After
Dy^+	3.5	4.5	8.2
Sq^+	2.6	3.2	3.9
FT	124.8	174.8	226.5
FrSc	3.5	3.5	7.2
FAD	2.1	3.8	3.4
$JuvC^+$	3.6	6.6	14.0
YFT^+	60.0	24.5	102.0
$FadC^+$	142.8	118.1	137.7

Outside No-take area				
ANOVA				
Indicator	Sum Sq	*df*	*F*	Pr(>*F*)
Dy^+	30.01	1	6.663	0.036
Sq^+	1.14	1	1.060	0.337
FT		1	12.141	0.010
FrSc	29.34	1	6.712	0.036
FAD	0.45	1	0.769	0.410
$JuvC^+$	122.24	1	1.255	0.300
YFT^+	13344.1	1	22.551	0.0021
$FadC^+$	850.9	1	0.343	0.576

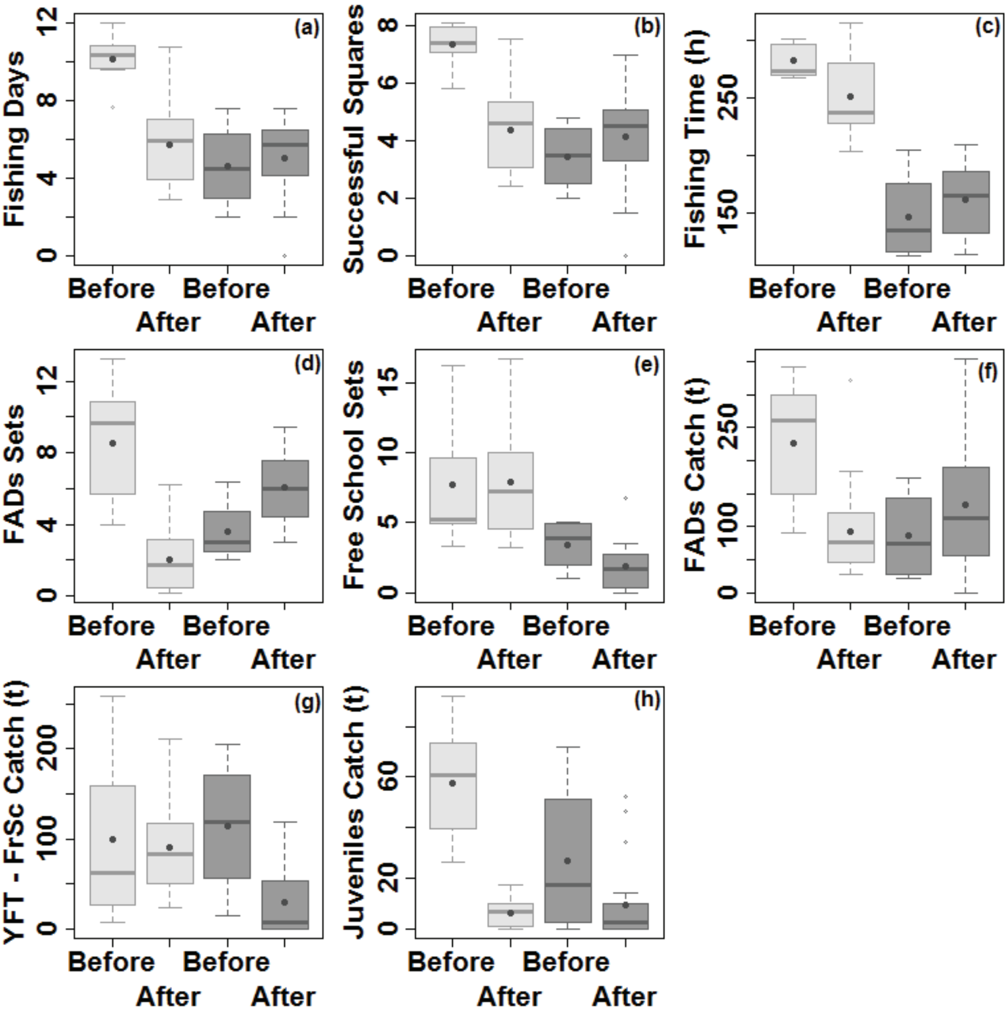

Fig. 2. Fishery indicators box-plot inside (light gray) and outside (dark gray) the moratorium on FAD for the three-month period before (1995–1997) and after (1997–2005). The average and the median are represented by points and stripes, respectively.

FAD than on free schools (Fig. 2d more detail in Fig. S1e, Appendix 2). Nevertheless, there was an increase in the number of sets on free schools in January (Fig. S1f, Appendix 2), while sets on FAD decreased, mainly inside the FAD moratorium area in the same months period (Fig. S1e, Appendix 2). Therefore, catches associated with each fishing method followed the same trend (Fig. 2f, g and Fig. S1g, h, Appendix 2). This pattern was similar for the catches of juveniles (<1.8 kg), during November–December 1995 and 1996 where the catches were the highest (Fig. 2h and Fig. S1d, Appendix 2). On the other hand, inside the moratorium on FAD zone the number of fishing days (Dy^+), the number of $1^\circ \times 1^\circ$ squares visited with catch (Sq^+), and the fishing time (FT) remained similar before the voluntary ban on FAD fishing entered into force (Fig. 2a, b, c, respectively, more detail in Fig. S1, Appendix 2).

3.1.2 After ICCAT recommendation

Once the voluntary moratorium on FAD followed by the ICCAT regulation was implemented, there were some changes in the patterns of the indicators analyzed (Fig. 2). During November to January, the fishing days (Dy^+) and the number of successful squares (Sq^+) depicted a similar trend, both within and outside the moratorium on FAD area (Fig. 2a, b) while, in contrast, fishing time (FT) reminded higher inside the area (Fig. 2c).

With respect to sets on FAD (*FAD*), there was a decrease inside the area, as expected. Nevertheless, this indicator increased outside and, specifically around the moratorium zone (Fig. 3e). Since recommendation [99-01], there were no further modifications and the measures established in this recommendation remained constant in the following years. It must be pointed out that when the voluntary moratorium on FAD was in force (until January 2000) the FAD sets were made principally outside (Fig. 3e). However, when ICCAT recommendation [99-01] entered into force, the EU fleet carried out this fishing method both inside and outside the zone (Fig. 3f).

The juveniles catch (<1.8 kg) inside the moratorium on FAD area was similar to that outside (Fig. 2h). On the contrary, the number of sets on free schools (*FrSc*) remained

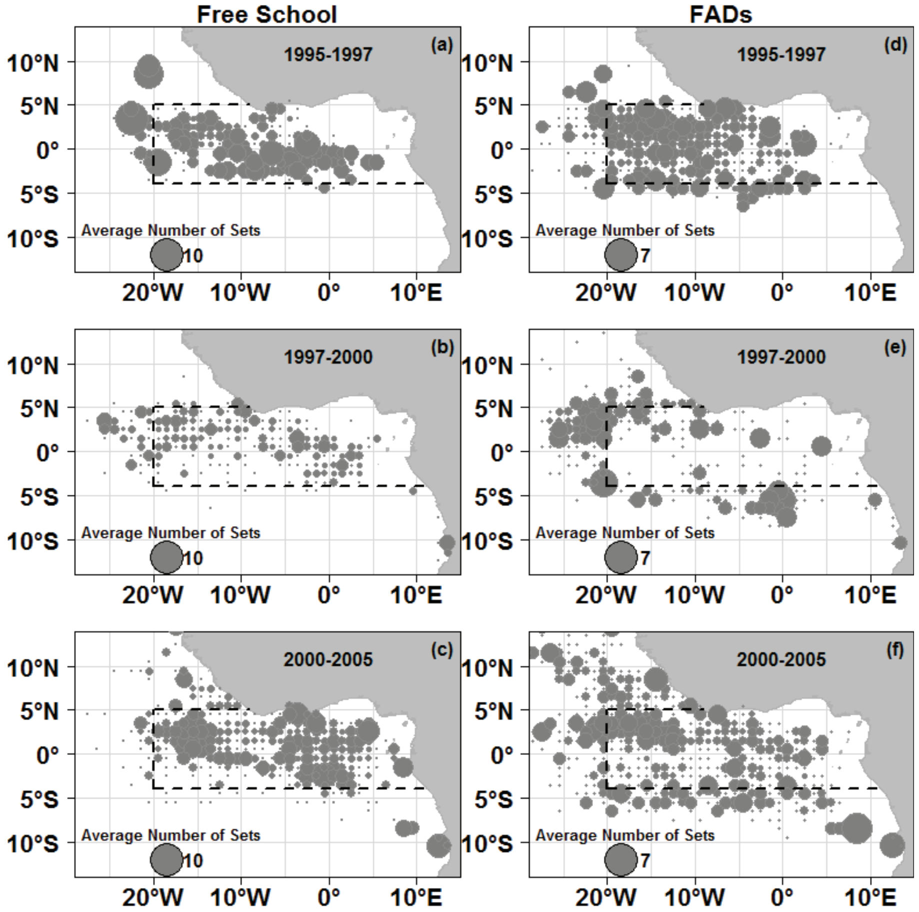

Fig. 3. Spatial distribution (only for the three-month moratorium on FAD) of the average number of sets on free schools and FAD (by 1° × 1° square); corresponding to (a, d) before moratorium for the period 1995–1997, (b, e) the EU purse seiners voluntary moratorium on FAD 1997–2000, and (c, f) after the moratorium on FAD adopted by ICCAT (recommendation [99-01]), 2000–2005. Dashed black lines correspond to moratorium area.

concentrated inside (Fig. 3b, c), reaching their peak in January; the same trend was logically observed for the catch of large yellowfin tuna on free schools (*YFT*$^+$) (Fig. S1f, h, Appendix 2).

3.1.3 Before-after approach

Because it was difficult to interpret interactions in a BA design, the analysis was conducted separately inside and outside the moratorium area.

Inside moratorium on FAD area

From the BA analysis applied to inside the moratorium area, significant differences were evident in almost all the indicators, except the number of sets on free schools (*FrSc*) and the catches of large yellowfin tuna associated with this method (*YFT*$^+$) (Table 2). The fishing days (*Dy*$^+$), the number of successful squares (*Sq*$^+$) and the fishing time (*FT*) decreased once the moratorium on FAD entered into force (Fig. 2a, b, c). Regarding the objective of the moratorium, there were significant differences in the number of sets on FAD (*FAD*) made inside the area and therefore FAD catches (Table 2) as well as juveniles catch (*JuvC*$^+$) (Fig. 2d, f, h).

Outside moratorium area

With regard to the outside region, only the number of sets on FAD (*FAD*) and the large yellowfin catch (*YFT*$^+$) differed significantly before and after the moratorium (Table 2). For the first indicator there was an increase, while the second decreased (Fig. 2d, g, respectively). Despite fishing days (*Dy*$^+$), successful squares visited (*Sq*$^+$) and fishing time (*FT*) decreased inside the moratorium area, no significant differences on these indicators were observed outside (Table 2). On average, the FAD catch (*FadC*$^+$) was higher after the moratorium, although this increase was not significant (at the 5% level) (Table 2).

3.2 Time-area closure

3.2.1 Before ICCAT recommendation

As mentioned in the Materials and Methods section, ICCAT prohibited all surface fishing activities inside the Picolo

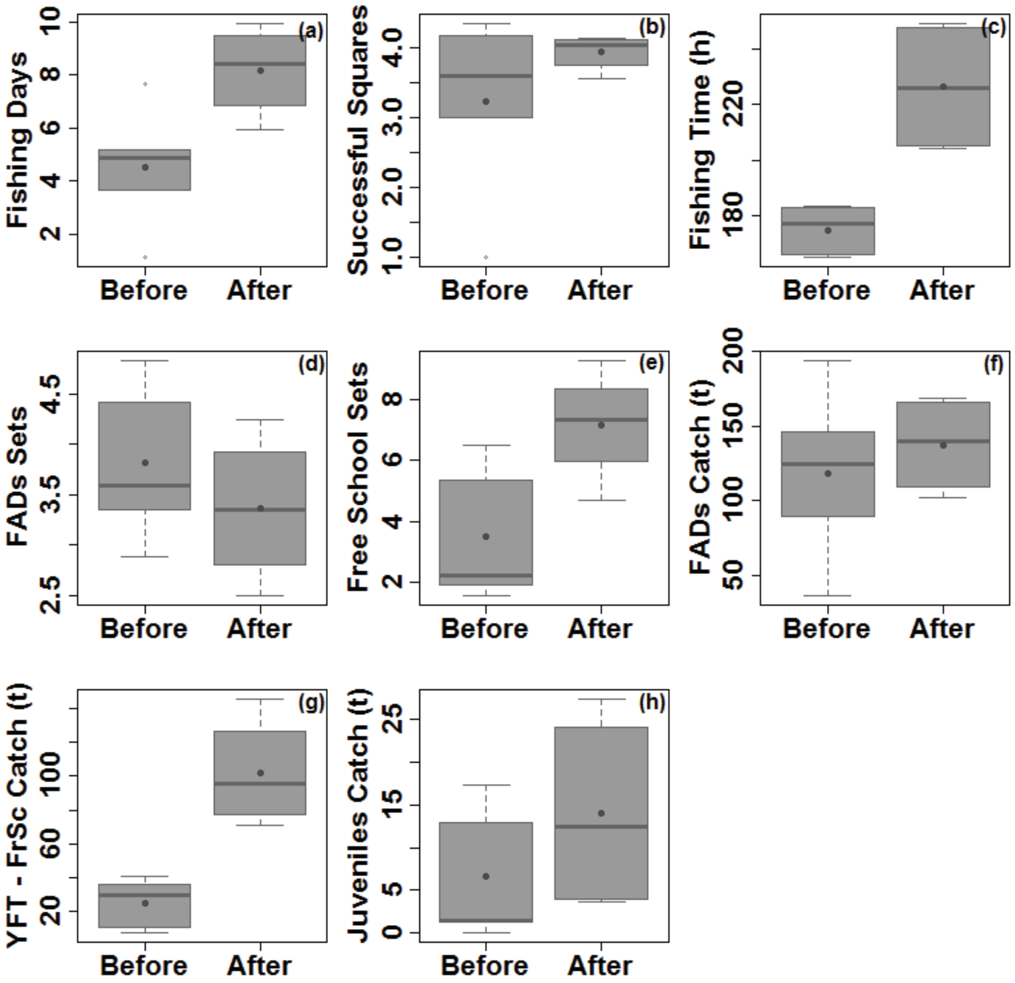

Fig. 4. Fishery indicators box-plot outside the Picolo zone for the regulation month (November) before (2000–2004) and after (2005–2008) the ICCAT recommendation [04–01]. The average and the median are represented by points and stripes, respectively.

area during the month of November after 2004; thus, fishery indicators were available and analyzed only outside no-take area. It should be noted that it was difficult to perceive the impact of such a small time-area closure (one month and a small area), while, on the contrary, the outside stratum was very large (Fig. 1). Despite this size difference, before the no-take area was established some indicators behaved in average similarly both inside and outside (Table 2). The large yellowfin catch on free schools (YFT^+) (Table 2, more detail in Fig. S2h, Appendix 2) and the FAD catch ($FadC^+$) (Table 2, more detail in Fig. S2g, Appendix 2) were both higher inside than outside the area, and this despite that the fleet spent more time outside than inside (Table 2). It should be noted that except the month of regulation the EU purse seine fleet had more activities outside the no-take area, but conversely, during the month of regulation (November), there was an increase in the fishery indicators (Fig. S2, Appendix 2). Only the catch of large yellowfin tuna and the corresponding number of sets on free schools (YFT^+ and *FrSc* respectively) did not present this general pattern (Fig. S2f, h, Appendix 2).

3.2.2 Before-after approach

Outside the closure area

The fleet increased its efficiency (i.e., days with catch) and fishing time significantly, but there was no difference in the number of successful squares visited (Table 2). The number of fishing days (Dy^+) increased significantly after the implementation of the spatial no-take regulation (Fig. 4a), while the effective area explored (Sq^+) remained unchanged (Fig. 4b). Unlike the situation observed during the moratorium on FAD, the number of sets on FAD (*FAD*) and the associated catch ($FadC^+$) did not increase (Fig. 4d, f, and Table 2).

In contrast to the slow increase in juveniles catch, there was a significant increase in the number of sets on free schools (*FrSc*) and their associated catches (YFT^+) (Fig. 4h, e, g, and Table 2). After the implementation of the closure area, the number of sets on free schools (*FrSc*) was located all around the Picolo area (Fig. 5b), while the sets on FAD (*FAD*) remained widespread throughout the area outside (Fig. 5d).

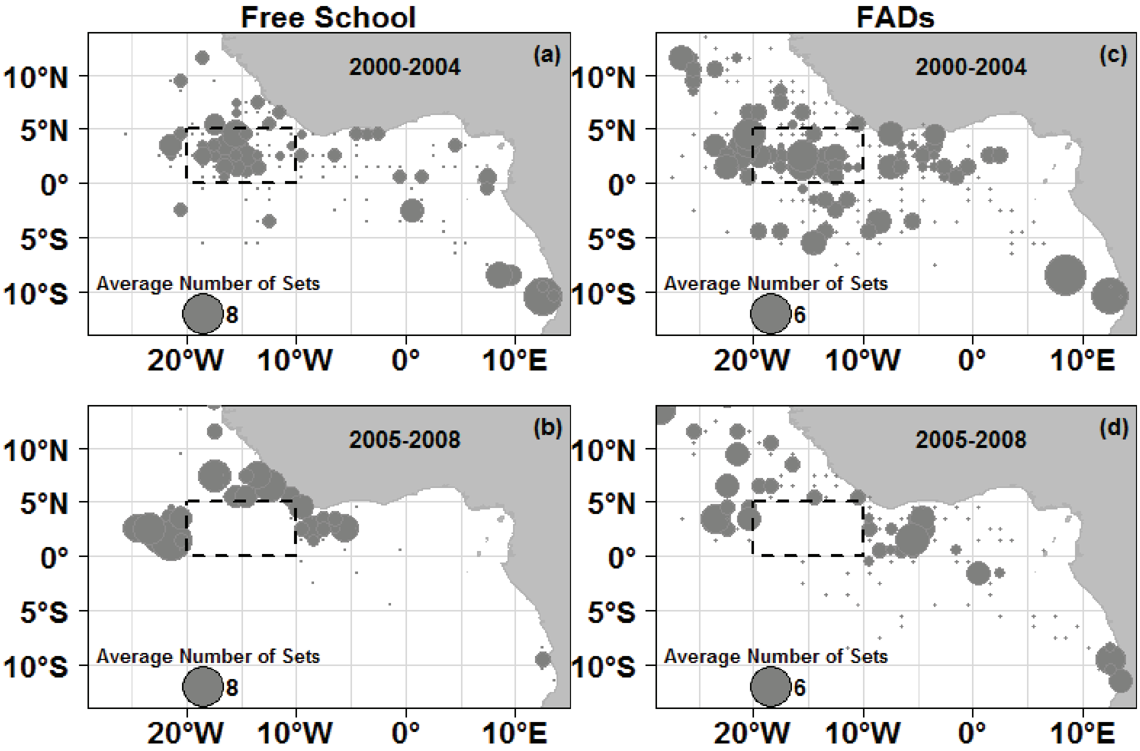

Fig. 5. Spatial distribution during the no-take regulation month (November) of the average number of sets on free schools and FAD (by 1° × 1° square); corresponding to (a, c) before the implementation of the no-take area in 2000–2004, and (b, d) after the ICCAT recommendation [04-01] for the period from 2005 to 2008. Dashed black rectangle corresponds to the Picolo no-take area.

4 Discussion

Marine protected areas (MPA) could be considered as a powerful tool to face ever-increasing over-exploitation of marine resources and deterioration of ocean habitats (Agardy et al. 2011). According with Hastings and Botsford (2003), MPA could have two fundamental objectives: preserve biodiversity and maximize fishery yields. The use of MPA, however, could have shortcomings, Agardy et al. (2011) mention five main types of such shortcomings: (1) MPA that as a result of their small size or poor design are ecologically insufficient; (2) inappropriate MPA plan or management; (3) MPA that fail due to the degradation of the unprotected adjacent areas; (4) MPA that do more harm than good due to unexpected consequences of management; and (5) MPA that seem to protect when in fact offer no such protection.

Furthermore, MPA should be selected on the basis of biological, oceanographic, physiographic, socio-cultural, political and economic criteria (Zacharias et al. 2006). Defining a time-area closure, in terms of no-take or prohibiting a specific fishing practice (e.g., FAD fishing), is not trivial, since the effectiveness of a spatial regulation for migratory fish depends on different factors such as: (1) the state of the stock; (2) some biological parameters (e.g., natural mortality of juveniles and exchange rates among fishing grounds); and (3) fishery characteristics (e.g., the fishery strategies developed due to the multi-species nature of the tropical purse seine fishery). In addition, it has been shown that in presence of catch quotas, as recently adopted for bigeye, seasonal or permanent closure area may have the unwanted effect of increasing effort in adjacent areas open to fishing (Dinmore et al. 2003; Hilborn et al. 2004) and consequently such regulation should be implemented in conjunction with other control measures (Horwood et al. 1998; Murawsky et al. 2000; Stefansson and Rosenberg 2005; Kaiser 2005; Jaworsky et al. 2006; Little et al. 2010).

The location and size of MPA are crucial issues which will determine the possible negative or positive effects from MPA enforcement, such as: (1) the reallocation of fishing effort outside the protected area; (2) MPA effectiveness facing oceanographic variability across space; (3) the time required for see the effects on stocks; and (4) the impact of overall higher total bycatch derived from the displacement of fishing effort to less productive areas (Zacharias et al. 2006).

In the mid 1990s, ICCAT was concerned about the large increase in the catch of bigeye tuna and juveniles due to the massive use of FAD since the early 1990s, as well as some indirect effects such as potential changes in migration patterns and in health indicators (i.e., concept of ecological trap; Hallier and Gaertner 2008) or the unexpected consequences on non-target associated pelagic species. Hence, ICCAT requested that further analysis be conducted on these issues to determine fishing areas and seasons with the objective of reducing the fishing mortality exerted on juveniles and specifically to mitigate the effect of the FAD fishing operations.

In response to this issue the EU purse seine fleet established, on a voluntary basis, a moratorium on the use of FAD that included a large area in the Gulf of Guinea in which high activities on FAD and juvenile catches were historically observed from November to January. However, the possibility of also targeting non-associated large yellowfin allowed the fleet to remain inside the moratorium area, which is evidenced by viewing the lack of changes in some fishery indicators such as fishing time, number of sets and yellowfin catch made on free schools before and after the moratorium. One may expect a shift in fishing mode due to the compliance of the moratorium and consequently an increase in the number of sets on free schools, but such a situation did not occur (i.e., inside the area the indicator remained at the same level while outside there was a no significant decrease). The lack of increase in the related activities could be due to the fact that it was not worth fishing on free schools until January, when the season for large yellowfin starts (Goujon 2004a). The increase in FAD sets was a way to compensate for the losses in catch inside the area due to the ban on FAD fishing. However, the gain in FAD catches outside the area was not significant from a statistical point of view, and this might be the reason why the fleet increased its activities with this fishing method inside the area during the last four years of the moratorium. It must be kept in mind that the EU purse seine fleet continued to fish on FAD but the catches on juveniles remained low in comparison to the catches before the moratorium. A possible explanation could be the skippers' ability to distinguish tuna schools that have only juveniles (Goujon 2004b).

The apparent stability in fishing time suggests that the fleet simply reallocated its effort to search and set on free schools. Nevertheless, our findings showed that the fishery indicators related to successful activities (fishing days, successful squares explored, catch of juveniles) decreased inside the area during the period of the moratorium on FAD. Since it is known that the moratorium stratum has been specifically designed to reduce FAD fishing, and bearing in mind the decrease in activities observed inside the area, one can conclude that the major part of the EU purse seine fleet respected the moratorium on FAD. However, few activities on FAD were observed, especially in November, which means an infringement of that regulation (Goujon 2004a; Goujon 2004b; Ariz et al. 2005; Ariz et al. 2009).

The absence of significant changes in the different indicators outside the moratorium area could be due to the fact that the EU fleet could continue to fish inside the area. However, although a comparison was not conducted between inside and outside the area for reasons explained in the Methods section, the results showed a barely significant increase in the number of sets with FAD outside the protected area (Table 2). This phenomenon has been described in other regulated fisheries with a spatial moratorium (Poos and Rijnsdorp 2007; Powers and Abeare 2009), but the related catches did not increase significantly, which suggests that it was not possible to compensate for the losses inside the area.

In general, the moratorium on FAD was more respected during the time that it was implemented on a voluntary basis (Fig. 3e, more detail in Fig. S1, Appendix) than it was formally established by ICCAT for all fleets. It must be stressed that the non-compliance of the FAD moratorium by some purse seiners operating under the flag of Ghana hindered the evaluation of this type of spatial regulation and limited the conclusions of management studies conducted by ICCAT (ICCAT 2009). Ariz et al. (2009) reported that landings of skipjack and bigeye tuna increased during the period of 2000–2003 inside the moratorium area with respect to before the regulation entered into force. These species are caught mainly on FAD and concern small sized tunas (Fonteneau et al. 2000).

Because of the IUU fishing activities, ICCAT modified the moratorium and a new time-area closure (termed Picolo area) entered into force in 2005. The Picolo area is known to support large concentrations of juvenile tunas likely due to oceanographic-specific conditions (Evans et al. 1981; Prince et al. 2010) and to the abundance of mesopelagic fishes, such as *Vinciguerria nimbaria*, which is one of the favorite preys of juvenile tunas in this region (Menard et al. 2000).

Compared to the moratorium on FAD strata, however, there was a large reduction in terms of space (by almost 25% of the surface of the previous regulation) and time (only November, i.e., 33% of the period of the moratorium). Another major change was the fact that the new spatial regulation referred to the restriction of all types of surface fishing activities.

Cass-Calay et al. (2006) and Brooks and Mosqueira (2006) indicated that the new closed area would result in an increase in catches of all species landed in the total Atlantic. The results here confirm these predictions. Effectively, the inside no-take area was respected, but there were some increases in the indicators outside the area. This may be due to the fact that it was possible to fish in a stratum that was known to have a high density of tropical tunas and fishing activities on FAD. Hence, there were no restrictions to fish with this method in the rest of the Gulf of Guinea and, as a result, the catches associated with this method were not expected to undergo any change. Nevertheless, the catch of juveniles increased in comparison to before the ban (Ariz et al. 2009). In general, it was difficult to account for the effects of this stratum since it was too small in surface and too short in time. Furthermore, within the framework of a BACI analysis, the results of the no-take area must be used with caution because the period that was considered as "before regulation measure" had already supported some restrictions in fishing activities (the Picolo area was included in the moratorium region on FAD).

According to the results, there is some evidence that this closed area resulted in an increase of the fishing activities of the EU purse seine fleet outside the area, and likely for other vessels operating in the eastern tropical Atlantic. This issue led ICCAT to reconsider the effectiveness of such a time-area closure to protect juvenile tunas, and some changes in surface area, in the time closure and in the restriction on FAD activities were considered (recommendation [08-01]). These changes would be a return to the moratorium that was established in 1997. This issue highlights the importance of defining the boundaries of a spatial regulation, especially in highly mobile species because most migratory species have some periods and/or zones in which they congregate and become vulnerable to fishing activities (Zacharias et al. 2006).

The use and effectiveness of area closures as a management tool have been estimated with respect to changes in community structure (Fisher and Frank 2002; Dinmore et al. 2003; Hiddink et al. 2006; Jaworsky et al. 2006), abundance species (Greenstreet et al. 2006; Lincoln-Smith et al. 2006; Smith et al. 2008; Jensen et al. 2010), yield resource (Holland and Brazee 1996; Holland 2003; Hart 2006), economic profits (Smith and Wilen 2003; Sanchirico et al. 2006; Armsworth et al. 2010). However, there are few studies that consider the fishermen component (Wilen et al. 2002; Murawsky et al. 2005; Kellner et al. 2007; Powers and Abeare 2009). Some authors (Johannes et al. 2000; Wilen et al. 2002; Salas and Gaertner 2004; Kaiser 2005; Branch et al. 2006; Poos and Rinsdorp 2007) noted the importance of taking into account fishermen's responses to management measures, basically because fishermen adapt their fishing practices to continue to catch the fish. Together with this, the effects on fishing effort (in terms of target species) and its spatial re-allocation as a response of fleet are logically evaluated. While in this study the nominal fishing effort showed almost no changes as a result of regulatory measures, when the analysis was conducted by fishing mode (in number of specific sets), it was possible to better understand the fishermen's responses to spatial regulations.

This study is an example of how different time-space management regulations (the moratorium on FAD and the no-take area) could have positive and negative effects on the fleet behavior and therefore on the target species. Johannes et al. (2000) mentioned the importance of considering the fishermen's ecological knowledge in making management decisions. Even if our objective was not to evaluate the effects of the voluntary basis moratorium (1997–2000), it seemed to have had better results in protecting the resource. On the other hand, we did not estimate both effects of the moratorium on FAD and the no-take area to the months of the year free of regulation measures. However, Ariz et al. (2009) reported a decrease in the annual total landings of the three principal species caught by the Spanish purse seine fleet since the moratorium on FAD, which may have led to some changes in fishing strategies. The important issue of how to manage the multispecies feature of the tropical purse seine fishery was also partially analyzed by Harley and Suter (2007). These authors estimated the potential to reduce purse seine bigeye catch considering no reduction in skipjack catch of a time-area closures on FADs in the eastern Pacific Ocean, finding that even with a decrease in bigeye catches it would be insufficient for sustainability.

One conclusion of this study is that as a complement to ecological information and population dynamic models, modeling the fleet dynamics is required to anticipate the fishermen's responses to different scenarios in regard to different spatial regulation measures, as well as to evaluate the effects of combining other management regulations with time-area closure.

Acknowledgements. The authors thank the anonymous referee for his constructive comments. This study is part of the Ph.D. thesis conducted by the first author (Torres-Irineo) at the University of Montpellier 2 (ED Sibaghe) and funded by CONACYT (Mexico), scholarship No. 199730. The authors also thank "Observatoire thonier" (IRD) for providing the logbook data.

Appendix 1: Before-After, Control-Impact (BACI) design

Data prior to an impact are normally difficult to obtain for evaluating its effect on most biological resources (Wiens and Keith 1995; Smith 2002). When historical data are available for the impact area, it is possible to compare means for samples from these data and periods after the event. If there is no such effect, it is expected that these means are equal, and if there is such an effect, a statistical difference is taken as evidence of effect (Underwood 1992; Wiens and Keith 1995; Smith 2002). This approach is called Before-After design (BA) which is without control locations to compare, and the observed changes could be due to causes other than the impact (Smith 2002). When conducting this design, it is assumed that the other factors besides the impact affecting a resource are homogenous during the whole period.

The statistical model for the analysis of data, X_{ik} is

$$X_{ik} = \mu + \alpha_i + \tau_{k(i)} \tag{1}$$

where μ is the overall mean, α_i is the effect of period (i = before or after), and $\tau_{k(i)}$ represents times within period. The statistical model for this analysis was the same as in Equation (1).

A variation of the above design is to sample more than one location in the impacted area, and it is suggested that some control locations be added to compare with the impacted area (Underwood 1992; Smith 1993; Wiens and Keith 1995; Smith 2002). This design is the BACI approach and consists in taking samples in all locations at replicated times before and after the event. Therefore, the BACI design consists of two treatments, (1) before-after, which is the main treatment, and (2) the control-impact (Smith 1993).

The implied model is

$$X_{ik} = \mu + \alpha_i + \tau_{k(i)} + \beta_j + (\alpha\beta)_{ij} + \varepsilon_{ijk} \tag{2}$$

where μ, α_i and $\tau_{k(i)}$ are the same as in the BA design and $(\alpha\beta)_{ij}$ is the interaction between period and location, and ε_{ijk} represents the remaining error.

However, normally there is only one location impacted. For this reason it is suggested to have more than one control location to permit evaluating with more certitude if the change was due to the impact and requires taking replicated measurements before and after the event in all the locations (Underwood 1992; Smith et al. 1993). Nevertheless, the response variable could be different from one location to another. For this reason, it is important to establish more than one control location to reach replication (Underwood 1992; Smith et al. 1993; Smith 2002). A further important fact is the temporal variation because the populations will not remain homogeneous all the time, and this could lead to some changes in the response variable (Underwood 1992; Smith et al. 1993).

In this study, the assessment of the effects on the purse seine fleet dynamics was conducted by a Before-After design, since it was not possible to define a control site because the outside area might also have been affected by the spatial regulation in different ways (e.g., changes in fishing effort over the years, large-scale environmental conditions, etc.) or even by the regulation per se.

Appendix 2

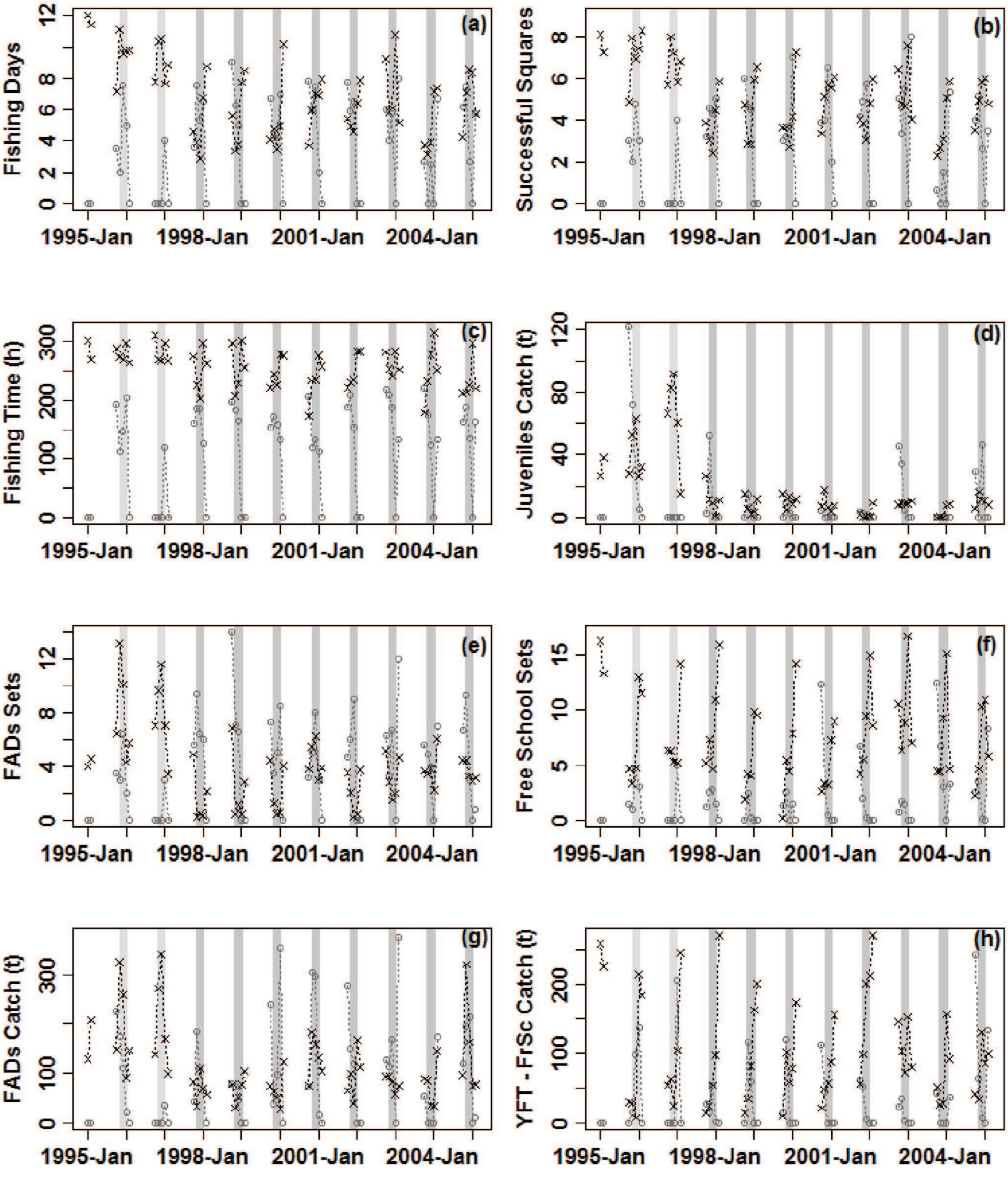

Fig. S1. Fishery indicators inside (-x-) and outside (-o-) during the three-month moratorium on Fish Aggregating Devices, FAD (± one month). Bars in light gray and bars in dark gray represent the restricted months before and when the moratorium on FAD was implemented, respectively.

Appendix 2: continued.

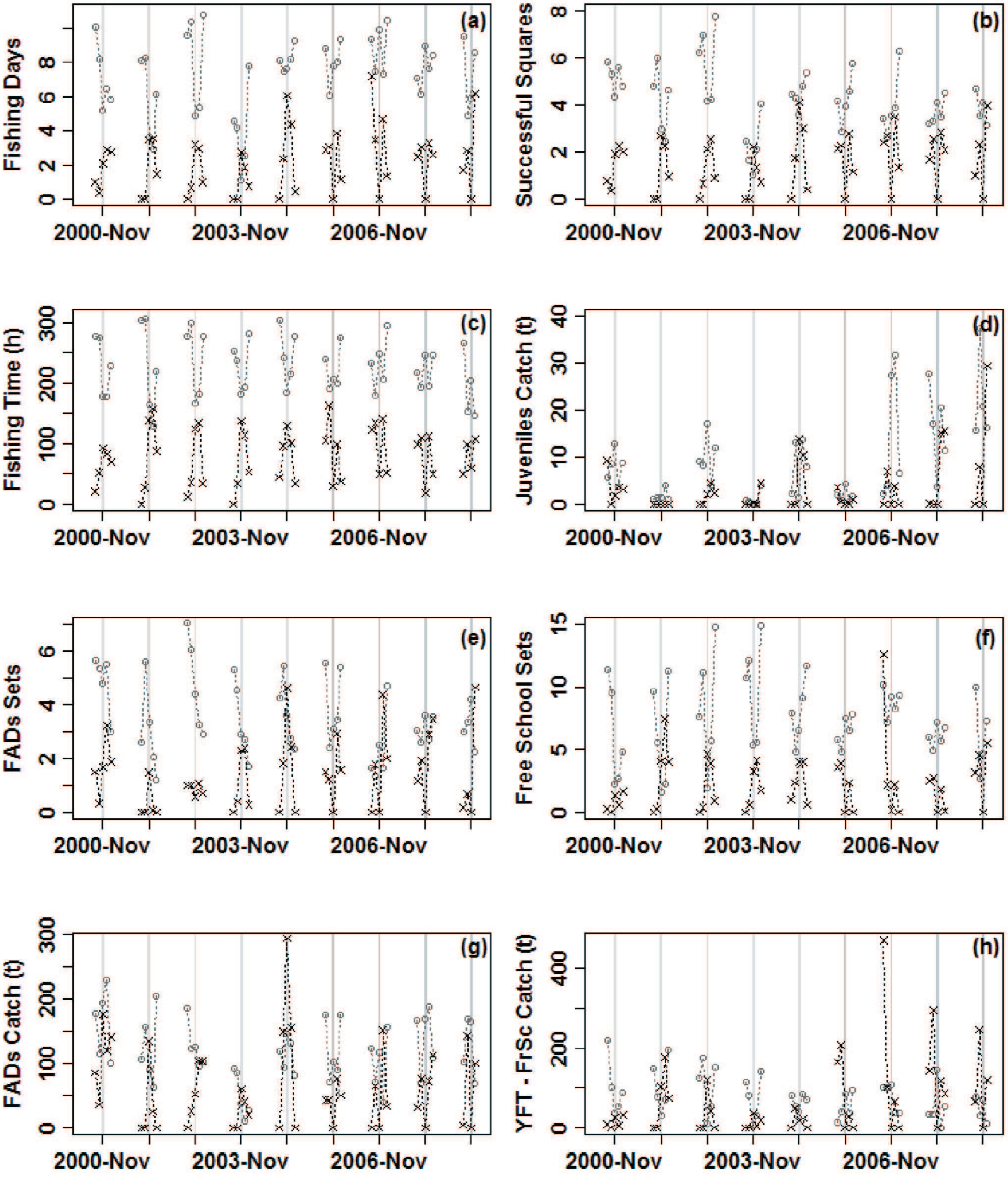

Fig. S2. Fishery indicators inside (-x-) and outside (-o-) during the regulation month of November (± two months) when the closure in the Picolo zone was established. Bars in light gray represent November before closure and bars in dark gray indicate when the regulation was implemented.

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