Évaluation de la durabilité écologique et socio-économique des pêcheries. Application aux pêcheries thonières tropicales à la senne

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Joël Aubin	Ingénieur de recherche, INRAE

“*Le sort des révolutions est lié à celui des femmes.*”

Françoise d’Eaubonne, Le Complexe de Diane, op. cit., p. 24.

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AVANT-PROPOS

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Elle a donné lieu à la rédaction de trois articles scientifiques tous les trois en premier auteur. A cette date, le premier article est en cours de révision en janvier 2024 dans la revue *Ecological Solutions and Evidence*. Le second est publié dans la revue *Science of the Total Environment*. Le dernier est le fruit d'une collaboration avec Arnaud Hélias et Thomas Cloâtre et nécessite encore une relecture par les co-auteurs avant soumission.

Lors de cette thèse plusieurs communications orales ont aussi été réalisées : présentation des travaux de thèse lors d'un colloque international à comité de sélection (YOUMARES, octobre 2021), deux séminaires d'unité (mars 2021 et mars 2023), deux journées thématiques de « l'IRD au Sud » (janvier 2023) et de « l'ACV à INRAE » (janvier 2024), une présentation aux Séminaire Marbec (avril 2023) ainsi qu'une présentation lors du colloque de l'Association Française d'Halieutique (juin 2022). Les travaux de thèse ont aussi été présentés lors d'un groupe de travail IFREMER en lien avec le projet SCEDUR : « Identification des indicateurs de durabilité de la pêche française ».

Un poster a été présenté aux journées de l'Ecole Doctorale des Sciences de la Mer et du Littoral (novembre 2023).

Lors de cette thèse, une expérience d'observatrice des pêches embarquée à bord d'un thonier senneur tropical de l'Océan Indien a été réalisée de janvier à février 2022.

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GLOSSAIRE (ANGLAIS ET FRANCAIS)

A
ACV: Analyse de Cycle de Vie
ALCA: Absolute Life Cycle Assessment
AP: Acidification Potential
ART: Artisanal
ATL: Atlantic Ocean

B
B0: Pristine biomass
B: Biomass
BB: Baitboat
BL : Banc libre

C
CCP: Climate change potential
CCSBT: Commission for the Conservation of Southern Bluefin Tuna
CFTO: Compagnie Française du Thon Océanique
CICTA: Commission Internationale de Conservation des Thons de l'Atlantique
CPCs: Members and co-operating non-Members to the Commission
CSTEP: Comité Scientifique, Technique et Economique des Pêches
CTOI : Commission des Thons de l'Océan Indien

D
DAS: Days at sea
DCF: Data collection framework
DCP: Dispositifs de concentration de poissons
DFG: Derelict fishing gear
DWFN: Distant water fishing nations

E
EEIOA: Environmentally-Extended Input-Output Analysis
EEZ: Exclusive economic zones
EF: Environmental footprint
EP, F: Eutrophication Potential in freshwater
EP, M & EP, T: Marine and terrestrial eutrophication
EU-PS: European tropical tuna purse seine

F
FAIR principles: Findable, Accessible, Interoperable and Reusable
FAO: Food and Agriculture Organization
FC: Facteur de caractérisation d'impact de la molécule
FD: Taux de dégradation (transfère dans un autre milieu et/ou dégradation)
FFA: Forum Fisheries Agency
FOS: Friend of the Sea
FPI: Fishery performance indicator
FRA-ATL: French fleet of the Atlantic Ocean
FRA-IND: French fleet of the Indian Ocean
FSA: Fish stock analysis
FTE: Full time equivalent
FUI: Fuel use intensity
FX : Exposition du milieu

G
GES : Gaz à effet de serre
GL: Gillnet
GT: Gross tonnage
GWP: Global warming potential

H
HCR: Harvest control rules

I
IEO: Spanish Oceanographic Institute
IND: Industrial
IND: Indian Ocean
INN: Pêche illicite non-déclarée et non réglementée
IPBES: Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

IRD: Institut de la Recherche pour le Développement
ISO: International Organization for Standardization
ISSF: International Seafood Sustainability Foundation

L

L50: Length at first maturity
LCI: Life cycle inventory
LCIA: Life cycle impact assessment
LL: Longline
LOG: Floating objects

M

MFA: Material Flow Analysis
MSC: Marine Stewardship Council

O

OD: Ozone Depletion
ODD: Objectifs du développement durable
ONG: Organisation non gouvernementale
ORGP: Organisation Régionale de Gestion des Pêches
Ob7: Observatory of exploited pelagic ecosystems

P

PB: planetary boundaries
PCA: Principal Component Analysis
PDF.year: Potentially disappeared fraction of species by year
PEF: Product Environmental Footprint
PM: Particulate matter
PRS: Post-release survival
PS: Purse seiner

R

RAPFISH: Rapid Appraisal Technique to Evaluate the Sustainability Status of Fisheries
RCP: Representative Concentration Pathway
RMD: Rendement Maximum Durable
RU,F: resource use, fossil
RoFTA: Return on Fixed Assets

S

SIDS: small island developing states
SKJ: Skipjack tuna (*Katsuwonus pelamis*)
SPA-ATL: Spanish fleet of the Atlantic Ocean
SPA-IND: Spanish fleet of the Indian Ocean
SSB0: pristine spawning biomass
SSB: spawning biomass
SSFDC: Coastal fisheries and particularly small-scale fisheries in developing countries
STECF: Scientific and Technical
SV: Supply vessel

T

T-LCA: Territorial Life Cycle Assessment
T: Ton
TAC: Total Admissible de Capture
TL: Trophic level

W

WBCSD: World Business Council for Sustainable Development
WD: Water depletion

K

kW: kilowatt

Y

YFT: Yellowfin tuna (*Thunnus albacares*)

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RESUME

La notion de durabilité des pêcheries renvoie aux objectifs pour le développement durable définit par l'ONU, qui entrecroise la sphère écologique, économique et sociale. Dans le cadre de cette définition internationale, une production durable des produits halieutiques se doit écologiquement soutenable, économiquement viable et socialement équitable.

La déclinaison de ces objectifs en indicateurs pour définir et évaluer les performances de durabilité des pêcheries est, d'abord, un enjeu méthodologique, auquel cette thèse propose de répondre en utilisant un cas d'étude de pêche maritime bien documentée, et pour lequel une grande quantité et qualité de données sont *a priori* disponible : la pêcherie thonière tropicale à la senne dans les océans Indien et Atlantique.

Cette pêcherie est composée de navires (des senneurs) arborant différents pavillons (différents pays exploitants) qui définissent des flottilles de pêche. Cette pêcherie existe depuis plusieurs décennies, plus ancienne dans l'océan Atlantique (début des années 1960) que dans l'océan Indien (milieu des années 1980) et est sujette à une gestion importante coordonnée par les Organisations Régionales de Gestion des Pêches (ORGPs) dans ces deux océans (la Commission Internationale de Conservation des Thons de l'Atlantique, CICTA et la Commission des Thons de l'Océan Indien, CTOI). Ces ORGPs contrôlent et archivent les données des Etats pêcheurs et rendent publique de nombreuses données halieutiques (captures par espèces, tailles de captures, efforts de pêche, etc.).

Dans la littérature scientifique, plusieurs approches existent pour évaluer la performance de durabilité des flottilles de pêche. Les plus utilisées sont l'approche tableau de bord d'indicateurs, d'une part, et l'approche d'analyse de cycle de vie (ACV), d'autre part.

En pratique, l'approche tableau de bord est très utilisée dans les démarches de labellisation des produits de la mer qui sont souvent des initiatives privées, avec des cahiers des charges hétérogènes. Il n'existe pas de tableau de bord faisant consensus pour évaluer la durabilité d'une activité de pêche. L'approche tableau de bord consiste en la déclinaison des différentes dimensions de la durabilité en critères de durabilité qui sont des jugements qualitatifs de ce que doit ou devrait être une pêche durable. Ces critères se déclinent en différents indicateurs

quantitatifs permettant d'évaluer le niveau atteint par chacun des critères de durabilité. Par exemple, pour répondre à la dimension environnementale de la durabilité des pêches, un des critères est l'exploitation des espèces cibles au Rendement Maximum Durable (RMD). Plusieurs indicateurs peuvent permettre d'évaluer cet objectif : écart entre la mortalité par pêche actuel et la mortalité par pêche permettant le RMD ou bien l'écart entre la biomasse actuelle de la ressource exploitée et de la biomasse attendue au RMD.

L'approche ACV est très utilisée pour évaluer les performances environnementales des produits, notamment alimentaires, grâce à un cadre méthodologique européen reconnu, et qui tend à se généraliser à l'évaluation environnementale des produits de la pêche et de l'aquaculture. Elle vise à évaluer l'empreinte environnementale d'un produit du « berceau à la tombe », c'est-à-dire de sa création à sa fin de vie. A chaque étape du cycle de vie du produit, l'ACV quantifie les flux d'intrants (ex. ressources, matières, énergies) et flux sortants (ex. polluants chimiques, gaz à effet de serre) vers les différentes écosphères (ex. atmosphère, hydrosphère, lithosphère) liés aux activités anthropiques. Sur la base de l'estimation de ces flux, l'ACV évalue leurs impacts potentiels pour l'environnement (ex. potentiel de changement climatique, d'acidification des océans, de dégradation de la couche d'ozone, etc.) et sur la santé humaine (ex. toxicité humaine, potentiel d'émissions de particules fines, etc.).

Aucune étude de recherche n'a, à ce jour, confronté ces deux approches sur un même cas d'étude afin de comprendre quelles en sont les complémentarités ou similitudes pour évaluer les performances de durabilité des pêcheries.

Cette thèse a donc deux enjeux majeurs :

Un enjeu méthodologique, d'une part, portant sur la complémentarité des démarches d'évaluation multicritères de type tableau de bord d'indicateurs et d'analyse de cycle de vie afin d'évaluer les performances de durabilité des pêcheries.

Un enjeu de gestion des pêcheries thonières tropicales, d'autre part, afin d'évaluer les performances de durabilité de ces pêcheries dans leurs dimensions écologique, économique et sociale, afin d'apporter des pistes de réflexion pour l'amélioration de leurs performances.

Le premier chapitre de cette thèse est une **introduction générale** qui porte sur le contexte méthodologique et réglementaire des approches d'évaluation multicritères appliqués aux produits de la mer, ainsi que sur l'historique des pêcheries thonières tropicales et leur principaux enjeux écologiques et économiques actuels. Il énonce la problématique et les questions de recherches associées qui se déclinent dans les chapitres suivants.

La thèse s'articule autour de trois articles scientifiques qui développent les deux approches et leurs applications.

Le **premier article** est un article méthodologique qui présente l'état des connaissances et de collectes de données disponibles sur les flottilles thonières, pour évaluer un certain nombre de critères et calculer des indicateurs de durabilité des pêcheries. Il illustre les possibilités pratiques actuelles de la mise en place d'un tableau de bord pour différentes flottilles (engins de pêche, taille de navires, etc.). Sur la base de ce tableau de bord, l'étude révèle que l'évaluation de durabilité socio-économique ne peut être renseignée que pour une minorité de flottilles (de pavillons européens) et sur des années récentes (2008-2020) due à un manque de données archivées par les ORGPs[1]. Le nombre d'indicateurs permettant d'évaluer la durabilité écologique des flottilles est en progression depuis les années 1950, notamment pour les flottilles industrielles, pour lesquelles plus de données biologiques sur les stocks exploités et halieutiques sur les flottilles sont disponibles.

Le **deuxième article** est une application du tableau de bord pour explorer la performance écologique des flottilles thonières tropicales industrielles (navires de pêche de longueur hors-tout supérieure à 40 m), ainsi que les performances de durabilité (écologiques, économiques et sociales) des flottilles de thoniers senneurs européens. La complémentarité d'indicateurs d'état des stocks avec des indicateurs d'impact sur les écosystèmes est mise en évidence. En moyenne sur la période 2015-2019, les senneurs et canneurs démontrent une meilleure performance environnementale que les fileyeurs et les palangriers. Ces derniers ont une sélectivité spécifique des captures plus faibles, et des captures accessoires de plus haut niveau

[1] Les ORGP proposent des données à collecter sur avis d'expert. Les Etats membres collectent la donnée et la font remonter aux ORGP qui contrôlent et archivent cette donnée.

trophique que les autres engins de pêche. Néanmoins les senneurs et canneurs ont un taux de capture de juvénile de thons plus élevé que les palangriers et fileyeurs. Les thoniers senneurs emploient différentes stratégies de pêche (sur banc libre – BL – ou sur dispositifs de concentration de poissons – DCP). Sur la période 2009-2019, les flottilles pêchant le plus sur BL ont des performances environnementales et sociales supérieures aux flottilles pêchant plus sur DCP. Sans données disponibles à l'échelle des stratégies de pêche, un lien direct ne peut être établi. Néanmoins, on démontre que la santé économique des flottilles thonières repose sur l'utilisation des DCPs, sur la période 2009-2019. Pour les pêcheries thonières tropicales européennes, les performances environnementales semblent ainsi être en conflit avec les performances économiques de court terme, sur la base des critères considérés et des indicateurs évalués. A long terme en revanche, il est établi que de bonnes performances environnementales, permettant la bonne santé écologique des ressources et des écosystèmes, sont un facteur essentiel de rentabilité économique des flottilles.

Le **troisième article** n'a pas encore été évalué par les pairs à ce jour et doit donc être utilisé avec précaution. Il présente les performances environnementales moyennes des flottilles de thoniers senneurs européens, sur la période 2015-2019, en utilisant l'approche Analyse de cycle de vie. Contrairement à la littérature existante sur ce même cas d'étude, les navires auxiliaires à la pêche, les DCPs (radeaux et bouées échosondeurs) ainsi que le trajet en avion des marins nationaux ont été pris en compte. L'étude démontre que les flottilles ont des sources d'impacts similaires attestant de leur homogénéité. La consommation de carburant est le contributeur majeur à plusieurs catégories d'impact dont le potentiel d'impact sur le changement climatique (plus de 85%). La consommation de carburant par les navires auxiliaires à la pêche contribue à 5 ± 7% aux impacts liés aux consommations totales de carburant, dont à l'impact potentiel de la pêche thonière à la senne sur le changement climatique. La construction des DCPs (radeaux et balise échosondeur) participe significativement à l'impact de la consommation en eau (8 ± 7%) et à la déplétion des ressources minérales et métalliques (10 ± 8%). Les engins de pêche (particulièrement le nylon composant les sennes) et le sel composant la saumure de conservation du thon à bord, participent majoritairement à la déplétion en eau (36 ± 12% et 22 ± 3% respectivement). Lorsque les impacts sont reportés à une même unité de production par stratégie de pêche (1 kilo de thon pêché sur BL et 1 kilo de thon pêché sur DCP), le thon pêché sur BL a un impact potentiel sur le changement climatique inférieur au thon pêché sur DCP, ce qui s'explique notamment par la prise en compte du coût environnemental des navires auxiliaires pour la pêche sur DCP. Néanmoins, cette différence significative est le fruit une hypothèse d'allocation d'effort qui rend les résultats incertains. L'étude des conséquences d'une variabilité interannuelle et inter-flottille sur ce résultat doit en particulier être poursuivie.

Une **discussion générale** en dernier chapitre clôture ce manuscrit de thèse. Elle en résume les conclusions principales et développe des perspectives d'études complémentaires pour l'évaluation de la performance de durabilité des pêcheries.

La méthode tableau de bord s'appuie sur des données existantes et permet un suivi annuel des pressions et impacts des pratiques de pêche ainsi qu'une analyse des critères et indicateurs à utiliser pour la gestion. Afin de répondre aux enjeux du développement durable, les indicateurs de performance de durabilité pourraient faire l'objet de futures recherches visant à évaluer les conséquences de divers changements des règles d'allocations des droits de pêche, actuellement fondés sur les droits historiques de chaque flottille. L'approche ACV permet de compléter le tableau de bord, notamment au regard des limites planétaires.

Finalement, les données actuellement archivées par les ORGPs des océans Atlantique et Indien ne permettent pas, à ce jour, d'évaluer les performances économique et sociale des flottilles de pêche en activité dans leur zone de compétence. En plus de ces données, les ORGPs devraient encourager la collecte de données par les Etats pêcheurs, et notamment de données concernant les consommations (e.g. carburant, matériaux) des navires, et améliorer la qualité des données sur les captures d'espèces accessoires et d'espèces sensibles, ainsi que les rejets. En particulier, notre analyse a montré que les captures d'espèces sensibles rapportées lors des pêches sous DCP apparaissait peu fiables et globalement sous-estimées.

La performance de durabilité des pêcheries thonières est fonction de l'engin de pêche et du métier de pêche exercé. L'apparente incompatibilité à court terme entre durabilité écologique et économique des thoniers senneurs amène aussi à questionner la pertinence des indicateurs utilisés (indicateurs de performance économique à court terme, manque d'indicateur de pollution plastique). De plus, le manque de données sociales et socio-économiques est mis en lumière et discuté au regard des objectifs pour le développement durable. Les différentes stratégies opérées par les thoniers senneurs (i.e BL et DCP) devraient donc être considérées comme différents *métiers* de pêche. Ainsi, susciter la collecte, contrôler, archiver et rendre publique des données halieutiques à l'échelle des métiers de pêche et des données sociales apparait comme une priorité pour l'évaluation de durabilité des pêcheries et de leurs pratiques.

Plus généralement, l'utilisation de l'ACV pour évaluer la performance environnementale des produits de la pêche est controversée, en raison d'une insuffisante prise en compte des enjeux de biodiversité. La thèse offre de ce point de vue des perspectives de recherche prometteuses, pour tester comment les indicateurs écologiques du tableau de bord, développés pendant la thèse, pourraient être intégrer au sein de la méthode ACV, ou agrégés dans une démarche synthétique regroupant les deux types d'indicateurs.

1. INTRODUCTION GÉNÉRALE

1.1. EVALUATION MULTICRITERE DE LA DURABILITE APPLIQUEE AUX PECHERIES RICHES EN DONNEES

1.1.1. La science de la durabilité au service du développement durable

Depuis plusieurs décennies, notre société fait face à l'accroissement des pollutions, la raréfaction des ressources naturelles et la surexploitation de la nature (Meadows et al. 1972). Donnella et Dennis Meadows introduisent pour la première fois le concept d'écodéveloppement qui vise à résoudre les effets négatifs d'un modèle de développement adopté après-guerre, au moment où les pays industrialisés s'engagent dans l'accroissement généralisé de la richesse individuelle et collective par la consommation (Lairez et al. 2020). C'est en 1987 que Gro Harlem Brundtland popularise, lors de la Commission mondiale sur l'environnement durable, le concept de développement durable : « Le développement durable doit satisfaire les besoins du présent sans compromettre la capacité des générations futures à satisfaire les leurs » (Brundtland 1987; Lairez et al. 2020). En 1992, lors du 3ème sommet de la Terre de Rio de Janeiro, cette définition est élargie aux trois piliers : le développement doit être à la fois économiquement viable, socialement équitable et respectueux de l'environnement afin qu'il reste vivable. Dix ans plus tard, la gouvernance sera ajoutée comme 4ème pilier du développement durable (Jégou 2007). En 2012, lors de la conférence de Rio+20, les signataires se mettent d'accord sur les 17 objectifs du développement durable (ODD), formellement adoptés à l'occasion de l'Assemblée générale des Nations Unies en 2015 (Figure 1.1). La pêche est notamment concernée par l'objectif n°14 dont l'intitulé étendu est « Conserver et exploiter de manière durable les océans, les mers et les ressources marines aux fins du développement durable ».

Parallèlement à ces objectifs institutionnels de développement, Clark et Dickson (2003) proposent de définir la science de la durabilité comme un nouveau champs disciplinaire de la recherche scientifique visant à mettre la science et la technologie au service d'une transition vers la durabilité. La science de la durabilité – « sustainability science » – se concentre sur les interactions dynamiques entre la nature et la société (Clark and Dickson 2003). Plus généralement, le terme de durabilité se définit différemment du développement durable. Pour Lairez et al. (2020) la durabilité désigne le caractère soutenable d'un modèle, que celui-ci soit économique, social, technique, etc. La durabilité caractériserait donc l'état d'un système et ses capacités à perdurer dans le temps. En ce sens, un système délétère pour l'environnement peut donc être qualifier de durable. Néanmoins, dans cette thèse, nous utiliserons les termes de durabilité ou « sustainability » pour qualifier un système dès lors qu'il répond aux objectifs du développement durable et est vivable, viable et équitable (Figure 1.2).

Figure 1.1.: Présentation des 17 Objectifs du Développement Durable considérés comme les objectifs du millénaire pour le développement depuis 2015 (ONU)

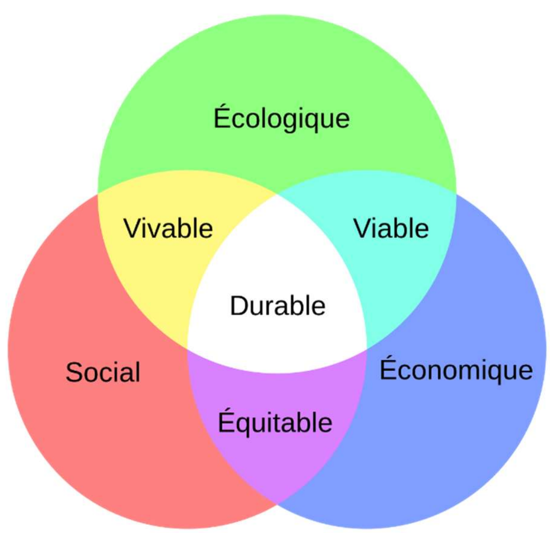

Figure 1.2: Vocabulaire employé pour qualifier la durabilité d'un système

La pêche est un mode d'extraction de ressources naturelles destinées à la consommation humaine en priorité, et participe ainsi à la bonne santé des populations humaines (sécurité alimentaire). Dans le même temps, cette activité est à l'origine ou contribue aux problématiques plus larges que sont la surexploitation des espèces exploités et l'érosion de la biodiversité, via son impact sur les écosystèmes et habitats marins (IPBES 2022; Mace 2014). Elle participe également au changement global due à l'utilisation d'énergie provenant de combustibles fossiles. L'IPBES identifie la pêche comme le premier facteur d'érosion de la biodiversité marine.

La pêche fait ainsi face à des problématiques diverses et à une disparité d'enjeux entre les pays du sud et pays du nord. Les pays du sud n'ont pas les mêmes moyens d'investissement et de régulation, faisant des pêcheries du sud les plus sujettes à la pêche illicite non-déclarée et non réglementée (INN). La collecte de données de qualité est également difficile rendant la gestion des stocks complexe. Les populations côtières des pays du sud dépendent fortement des produits de la mer comme source unique de protéines alors même qu'un accroissement de leur démographie est attendue, particulièrement en Afrique de l'Ouest et Centrale (FAO 2022). Afin de répondre aux attentes des ODD, il est essentiel d'opérer une transition vers une pêche plus durable qui considère les enjeux écologiques, économiques et sociaux.

1.1.2. Les approches multicritères d'évaluation de la durabilité et définitions

L'initiation de cette transition peut être opéré à différentes échelles. A l'échelle politique, des changements de la réglementation commune peuvent induire des changements de pratique. La mise en place de réglementation nécessite un arbitrage politique. Appliqué à la pêche, il peut s'agir de quotas de pêche (Total Admissible de Capture – TAC) ou de moratoire (fermeture spatio-temporelle à la pêche). A l'échelle individuelle, les systèmes de production, comme des entreprises de pêche, peuvent décider de s'auto-impliquer dans une démarche plus vertueuse. Ces démarches peuvent être soutenues ou orientées par des subventions, sous-entendant une implication politique sans volonté de régulation contraignante.

Finalement, le marché, régulé par l'offre et la demande peut être une opportunité de changement. Afin que la demande en produits de la mer durables incite à un changement de pratique, les labels proposent au consommateur la garantie d'une consommation responsable suivant un cahier des charges, autrement dit, considérant un certain nombre de critères supposés définir une pêche durable. De nombreux labels existent, largement dominés par une « consonance » environnementale (Tableau 1.1). Face à des attentes sociétales en évolution, d'autres labels mettent en avant les dimensions sociales des modalités d'exploitation et de transformation. Le label Marine Steward Council (MSC)[2] est le label pêche le plus connu dans le monde, même si une partie des consommateurs disent ne pas le connaître (10 à 30% - Maesano et al., 2020). Les labels utilisent des approches multicritères à des fins de communication (promouvoir des actions, valorisation des pratiques), la certification étant la résultante d'une décision multicritère.

Plus généralement, l'évaluation multicritère permet de formaliser et de rendre compte du degré d'atteinte des enjeux du développement durable (sous-entend un objectif défini) et d'orienter les systèmes de productions vers une voie plus durable. La définition du cadre conceptuel est essentielle à une démarche multicritère car il explicite la vision du développement durable retenu. Il fait le lien entre les dimensions du développement durable, leur déclinaison en critères et l'élaboration des indicateurs. Les critères sont des variables qualitatives qui décomposent la notion de développement durable en sous-éléments et qui servent de base à l'évaluation. Il peut s'agir par exemple d'un critère de rentabilité économique d'une pêcherie ou de maximisation de la sélectivité spécifique des captures. C'est le niveau de cette rentabilité ou de cette maximisation qui participe au niveau de la durabilité in fine. Les indicateurs permettent de mesurer ou d'estimer les critères. Dans l'exemple du critère de rentabilité économique, les indicateurs possibles, sans être exhaustifs, sont : la marge brute, le profit net, l'excédent brut d'exploitation ou encore le retour sur capital physique (RoFTA).

[2] MSC est une ONG internationale à but non lucratif créée en 1997 par l'ONG WWF et le groupe Unilever afin de « lutter contre la surpêche et pour la préservation des océans en encourageant les pêcheurs et la filière à adopter des pratiques environnementales plus durables » (MSC 2023).

Tableau 1.1: Présentation synthétique des labels les plus communément retrouvés pour des produits de la pêche, notamment sur le marché français. ACV : Analyse de cycle de vie. DCP : Dispositif de concentration de poisson. INN : Pêche illicite non-déclarée et non réglementée. TAC : Total admissible de capture. RMD : Rendement maximum durable. Élaboration personnelle ; liste non exhaustive.

Nom des labels, origines et date de création	Certification	Environnement	Social	Gouvernance	Qualité
Ecolabel « MSC » - Marine Steward Council - 1997	oui	. Ressource (stocks gérés au RMD) . Ecosystème : Impact minimisé	/	. Gestion efficace des pêcheries	/
Label "Fair Trade" – FAO - 1997	non	/	Commerce equitable	/	/
Ecolabel "Dolphin Safe" (spécifique aux pêcheries thonières) – 1990	non	. Ecosystème : Limiter les prises accessoires de dauphins	/	/	/
Ecolabel suédois et norvégien "Krav" – 2004	oui	. Ressource : Evaluation des stocks (RMD) . Environnement : Données collectées sur les navires (déchets, consommations, etc.), approche ACV	. Responsabilité sociale (droits de l'homme et de l'enfant)	. Respect de la législation	. Traçabilité
Ecolabel Allemand "Naturland Wildfish" - 2007	oui	. Ecosystème (sélectivité, Captures accidentelles, habitats)	. Conditions de travail . Droit du travail . Commerce équitable	. Respect de la législation . Communication de données de captures	/
Label Friend of the Sea – FAO – 2008	oui	. Ecosystème (Stock non surexploités (norme FAO), sélectivité, pas de capture accessoire vulnérable (liste IUCN), DCP non emmêlant . Environnement : gestion des déchets et de l'énergie	. Responsabilité sociale	. Respect des exigences légales (TAC, pas de pêche INN, maillage, taille minimale)	. Traçabilité
Ecolabel français « Pêche Durable » - 2017	oui	. Ecosystème (état des stocks, sélectivité, habitats) . Environnement (réduction de carburant, gestion des déchets, prévention des pollutions)	. Conditions de vie à bord (sécurité et formation des équipages) . Rémunération	/	. Niveau élevé de fraîcheur

Les méthodes d'évaluation sont des cadres d'analyse reposant sur un ensemble de règles prédéfinies et sur une liste organisée d'indicateurs et de critères. Deux méthodes d'évaluation multicritère sont classiquement utilisées pour la durabilité des pêcheries, et régulièrement appliquées à l'évaluation environnementale des systèmes de production alimentaires :

1. Les approches tableau de bord qui reposent sur une liste de critères qualitatifs de durabilité des pêcheries (cadre conceptuel) et d'indicateurs quantitatifs associés (cadre méthodologique) permettant de juger de l'atteinte de ces critères par la définition de seuils. La méthode RAPFISH (Pitcher and Preikshot 2001) est un exemple d'analyse multicritère de la durabilité des pêcheries qui aborde les dimensions écologique (état de stock, environnement), économique (facteurs économiques macro et micro), éthique (au sein des industries et des communautés), sociale (facteurs anthropologique et sociaux) et technologique (caractéristiques des pratiques, engin de pêche), reconnu dans la littérature scientifique (Suresha Adiga et al. 2015; Lloyd Chrispin et al. 2022; Chaliluddin et al. 2023);

2. L'analyse de cycle de vie (ACV ; ISO, 2006) qui évalue les impacts environnementaux d'un produit tout au long de son cycle de vie, c'est-à-dire de la fabrication des matières premières jusqu'au traitement en fin de vie du produit. Par exemple, de la construction des navires de pêche jusqu'à l'étape de consommation d'un filet de poisson et la fin de vie de l'emballage. Elle prend en compte les étapes intermédiaires (ex. production, transport, consommation). Le cadre de la méthode ACV est normalisé depuis 1997 (ISO 14040-40) mis à jour en 2006 (ISO 14040-44). La méthode ACV est présentée, par un exemple d'impact, dans le paragraphe suivant et sera détaillée au chapitre 4 de la thèse.

Plus précisément, la méthode ACV quantifie, à chaque étape du cycle de vie du produit, les flux d'intrants (ex. ressources, matières, énergies) et flux sortants (ex. polluants chimiques, gaz à effet de serre) vers les différentes écosphères (ex. atmosphère, hydrosphère, lithosphère) lié aux activités anthropiques. Sur la base de l'estimation de ces flux, l'ACV évalue leurs impacts potentiels pour l'environnement (ex. potentiel de changement climatique, d'acidification des océans, de dégradation de la couche d'ozone, etc.) et sur la santé humaine (ex. toxicité humaine, potentiel d'émissions de particules fines, etc.). Par exemple, l'émission de gaz à effet de serre (GES) dans l'atmosphère induit un impact potentiel (changement climatique) qui est fonction de la quantité de GES émise et d'un facteur de caractérisation d'impact de la molécule (FC) (Equation 1). Ce FC est fonction de l'effet potentiel de la molécule de GES (pouvoir réchauffant ou forçage radiatif) (FE), son taux de dégradation (transfère dans un autre milieu et/ou dégradation) (FD) et l'exposition du milieu (proportion de l'émission atteignant l'atmosphère) (FX) (Equation 2).

(1) $Impact = Emission_{air,\ eau,\ sol} . FC$

(2) $FC = FE\ .\ FD\ .\ FX$

L'impact potentiel peut ainsi être représenté comme l'intégrale un effet physico-chimique au cours du temps (Figure 1.3).

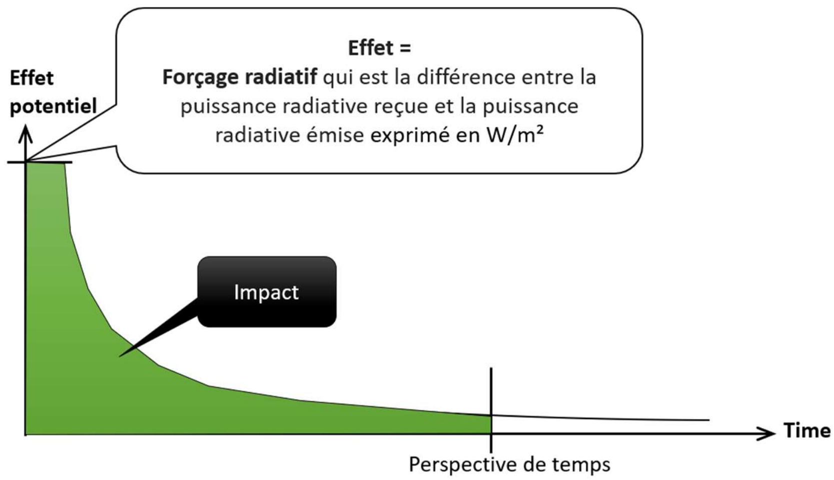

Figure 1.3: L'impact vue par l'approche ACV. Adapté de la formation ACV par la Chair ELSA PACT.

1.1.3. Contexte scientifique et réglementaire de l'approche multicritère appliquée aux pêcheries

L'intensification des pressions anthropogéniques sur les écosystèmes a conduit à développer l'évaluation environnementale des activités économiques et humaines depuis plusieurs décennies, notamment via la méthode d'ACV (H. Smith 1963 ; Leontief 1970 in Bjørn et al. 2018). En 2013, l'Union Européenne a proposé une méthode harmonisée de l'approche ACV pour l'évaluation environnementale des produits : la méthode PEF ou « Product Environmental Footprint » (European Commission 2013). L'objectif étant à terme de contraindre le secteur tertiaire à répondre plus efficacement aux enjeux de durabilité environnementale (European Commission 2021). Il existe plusieurs initiatives en cours, proposant des recommandations pour l'application de la méthode PEF pour les produits de la mer (Life Aquapef ; Marine Fish PEFCR), mais qui n'ont pas été encore officiellement validées.

Pour les écosystèmes marins, plusieurs études ACV ont été menées pour estimer la durabilité des systèmes de pêche (e.g. Abdou et al. 2018; Avadí and Fréon 2013; Laso et al. 2018; Ramos et al. 2011; Ziegler et al. 2018; Vázquez-Rowe et al. 2012). Ces approches permettent en particulier d'évaluer les impacts de la pêche sur le changement climatique ou sur l’eutrophisation des eaux. Nombreux sont les auteurs à mettre l’accent sur le besoin de méthodes permettant d’intégrer à cette évaluation une prise en compte systématique des impacts biotiques de la pêche, sur les ressources, les habitats, la biodiversité, etc. (Cashion et al. 2016; Emanuelsson et al. 2014; Hélias, Langlois, and Fréon 2018). Par ailleurs, la gestion des pêches à l’échelle européenne se base sur les objectifs de la FAO (FAO 1995) qui promeuvent une démarche globale associant des considérations sociales et économiques aux impacts environnementaux, en lien avec les objectifs du développement durable.

De son côté, l’approche tableau de bord a été utilisée dans plusieurs études pour développer des outils de gestion des pêches associant ces trois composantes – écologiques, économiques et sociales – (Anderson et al. 2015; Danto et al. 2021; Dewals and Gascuel 2020; Kinds et al. 2016; Pitcher and Preikshot 2001). Néanmoins, une méthodologie opérationnelle, intégrant à la fois des indicateurs de type tableau de bord et des indicateurs d’ACV, n’est pas encore disponible (Ziegler et al. 2016). Ce manque de gestion intégrée pour une pêche durable s'explique notamment par les priorités politiques, les différences régionales dans les systèmes de gestion, la disponibilité des données et le manque d'informations (Ziegler et al. 2018). Récemment, un groupe de travail du Comité Scientifique, Technique et Economique des Pêches (CSTEP) a proposé une méthode pour un affichage environnemental des produits de la mer intégrant des indicateurs de gestion des pêches, de l’ACV ainsi que quelques indicateurs sociaux (Gascuel et al. 2021), laissant cependant à la marge les indicateurs économiques.

De nombreux auteurs montrent par ailleurs, qu’il existe une forte variabilité interannuelle des performances de durabilité des pêcheries (Basurko et al. 2023; Codotto et al. 2023; Ziegler et al. 2018; Avadí et al. 2014) liée à un environnement marin et économique fluctuant (Laso et al. 2018; Hornborg et al. 2022) et préconisent un suivi des performances dans le temps. Néanmoins, à notre connaissance, l’étude de la coévolution des indicateurs de durabilité sur le long-terme (plus de 5 ans), et prenant en compte les dimensions écologiques, économiques et sociales, est à ce stade inédite pour un cas d’étude sur la pêche.

Un travail de suivi des performances peut faire l’objet d’agrégation multicritère grâce à des méthodes de pondération entre les critères ou d’arbres de décisions qui nécessiterait un arbitrage entre les critères et indicateurs (Danto et al. 2021; Dewals and Gascuel 2020; Lairez et al. 2020), ce qui ne fera pas l’objet de cette thèse.

Pour répondre à ces enjeux d'évaluation multicritère et de suivi, la thèse se focalise sur un cas d'étude bien documenté : les pêcheries thonières tropicales, car elle nécessite une grande quantité et qualité de données, qu'elles soient d'ordre environnementale (données biologiques sur les stocks exploités, l'impact sur la biodiversité, les consommations, la conception des navires, etc…) mais aussi sociales et économiques.

1.2. Les pecheries des thons tropicaux dans les oceans Atlantique et Indien

Dans l'océan mondial, les pêcheries[3] thonières, et les stocks[4] qu'elles ciblent, sont très étudiés et font l'objet d'une gestion rigoureuse en raison de leurs volumes de capture élevés, de leur grande valeur économique (FAO 2022). Les pêcheries thonières ciblent des grands pélagiques de la famille des *Scombridae,* principalement les thonidés. Les thonidés ont pour caractéristiques d'être hautement migrateurs, grégaires et prédateurs. Ces espèces sont une source importante de protéines, de micronutriments essentiels et de revenus pour des millions de personnes, dont beaucoup vivent dans des pays à faible revenu ou en développement (FAO 2020; McCluney, Anderson, and Anderson 2019; Xie et al. 2020).

Les thonidés sont économiquement séparés en deux groupes, les thonidés majeurs et les thonidés mineurs. Les thonidés mineurs encore appelés thons néritiques, sont côtiers sans déplacements de grande amplitude et surtout exploités par les pêcheries artisanales des Etats côtiers. Les thonidés dits majeurs sont les cibles des pêcheries industrielles dans l'océan mondial. Dans cette thèse, l'appellation de « thonidés » fera référence au thonidés majeurs et l'appellation de « thonidés tropicaux » regroupera les espèces de thonidés majeurs tropicaux : le listao (*Katsuwonus pelamis*), l'albacore (*Thunnus albacares*) et le thon obèse (*Thunnus obesus*). En 2020, la capture globale des sept principales espèces de thons dits majeurs, le germon (*Thunnus alalunga*), les thons rouges (*Thunnus thynnus, Thunnus maccoyii* et *Thunnus orientalis*), le listao, l'albacore et le thon obèse, était de 4,8 millions de tonnes soit

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[3] Une pêcherie est un ensemble de navire de pêche ciblant le(s) même(s) stock(s) en utilisant le même engin de pêche.

[4] Un stock correspond à la part exploitable (recrutée) d'une espèce donnée dans une zone donnée. Le stock n'inclut pas les stades avant recrutement (larves, alevins).

près de 6% des captures marines mondiales. Les thons tropicaux majeurs (listao, albacore et thon obèse) sont les espèces les plus pêchées, notamment le thon listao qui est la première espèce marine exploitée en valeur. Les proportions des différentes espèces dans les débarquements mondiaux s'élèvent à 57% pour le listao, 29% pour l'albacore et 8% pour le patudo (FAO 2022).

1.2.1. Les différents engins de pêche ciblant les thons majeurs – Adapté de Seret et al. (2023)[5]

« Dans tous les océans, la technique de pêche la plus productive est la pêche à la senne, représentant 66% des débarquements. […] Les contributions des autres engins de pêche s'élèvent à 10% pour la palangre, 7% pour la pêche à la canne, 4% pour les filets maillants et 13% pour les engins divers tels que ligne de traîne, ligne à main ou palangrotte. […]

Une palangre qui est une ligne principale, dite mère, équipée de plusieurs centaines d'hameçons. La palangre pélagique qui capture des thons et autres grands pélagiques est dérivante. La palangre dérivante est utilisée pour cibler l'albacore, le germon, l'espadon mais surtout le thon obèse et thon rouge. Elle peut mesurer jusqu'à 100 km et porter jusqu'à 3 500 lignes secondaires munies d'un hameçon. […] La palangre est composée d'une ligne mère en nylon […] qui porte des bas de ligne ou avançons de 10 à 30 m de longueur […]. A chaque extrémité de la palangre, ainsi qu'à divers autres endroits, des bouées émettrices sont disposées pour localiser la ligne après sa dérive lorsque la décision de ma virer sera prise. […]

La pêche des thons à la canne, appelées aussi pêche à l'appât vivant […] consiste à attacher à l'extrémité de la canne un fil en nylon équipé d'un hameçon. […] La canne, traditionnellement en bambou est désormais en fibre de verre, et mesure entre 2 et 5 m de long. […] Lors des opérations de pêche, de l'eau de mer est aspergée au-dessus du banc pour simuler un bouillonnement lié à une frénésie alimentaire. La réussite de la pêche des thons à la canne réside dans la qualité des anchois, sardines, maquereaux utilisés comme appâts vivants. Ces derniers sont régulièrement jetés au-dessus du banc[6] pour maintenir l'association entre le

[5] Avec accord des auteurs

[6] Opération appelée « chumming »

banc de thons et le bateau appelé canneur. Les pêcheries à appât vivant ciblent notamment des thons tropicaux listao et albacore dans l'ouest de l'Océan Atlantique tropical, dans l'est de l'océan Indien tropical et l'ouest de l'océan Pacifique équatorial. […]

La pêche au filet maillant dérivant est une activité traditionnelle de pêche de poissons vivant en groupes ou en bancs […]. Le filet pend verticalement avec une ralingue de dos équipés de flotteurs et une relingue de bas avec des plombs pour assurer la verticalité du filet. […] Jusqu'aux années 1950, ces filets sont fabriqués à partir de matériaux organiques tels que le chanvre ou le coton. […] Le nylon monofilement, [d'une plus grande longévité], remplace les matériaux biodégradables et la taille des mailles diminue. […] Des effets collatéraux de la mégafaune marine (requins, raies, mammifères marins, tortues marines, oiseaux marins) engendrés par ces filets [conduira] à l'interdiction des filets dérivants de plus de 2.5 km de long dans les eaux internationales en 1992.

La pêche à la senne est une technique de pêche […] destinée à capturer des poissons en bancs en pleine eau. […] Le principe de fermeture du filet par le bas grâce à une coulisse apporte une redoutable efficacité au piégeage. L'ensemble du banc se retrouve dans la poche qui se referme au fur et à mesure de la remontée du filet. Le poisson dans la poche est récupéré à l'aide d'une salabarde ou de pompes [puis est mis en cale]. Cette pêche de thons à la senne débute aux Etats-Unis et arrive en Europe en 1964. […] Les senneurs océaniques [ont connu], eux aussi, des modifications régulières de leur et motorisation. De nos jours, les senneurs sont des bateaux de 60 à 120 mètres de longueur hors tout, avec des motorisations comprises entre 3600 CV et 8 600 CV. La senne est un filet d'une superficie de 40 hectares[7] avec une longueur de 2 000 m, une hauteur de 200 m et des mailles de 15 cm de côté. Lorsque le banc est repéré, l'embarcation annexe appelée « skiff » fixée à l'arrière du senneur déroule la senne en encerclant le banc. Une opération de filage, puis de virage de la senne avec la mise à bord de plusieurs dizaines de tonnes de thons dure entre 15 et 30 minutes. Pour la recherche des bancs, le senneur utilise plusieurs technologies : des jumelles d'une portée pouvant atteindre 10 km, des radars pour détecter des groupes d'oiseaux marins à 60 km, un sondeur vertical et

[7] Soit 80 terrains de football

un sonar latéral avec des portées de 3 à 500m, des cartes satellites avec divers indicateurs de présence dans bancs comme la température de surface, la vitesse et la direction du courant, l'anomalie de hauteur d'eau et la profondeur de la thermocline.

Le thon est traditionnellement pêché par les senneurs lorsqu'ils sont en banc libre ou en association avec des mammifères marins, requins-baleines ou des objets flottants naturels (troncs d'arbres, branches) sous lesquelles les thonidés et autres espèces pélagiques ont un comportement d'agrégation (Dupaix et al. 2022). Des objets flottants artificiels (ex. déchets plastiques) peuvent également permettre l'agrégation des thons.

Afin de reproduire artificiellement ce comportement d'agrégation, des structures, prenant généralement la forme d'un radeaux flottant et d'une partie immergée plus ou moins complexe, ont été développées pour agréger le thon. En fonction de la localisation (côtière ou haute mer), ces radeaux peuvent être ancrés ou dérivants et construits en différents matériaux (structure en métal, en bambou, etc.). Le plus communément utilisé par les thoniers senneurs sont les dispositifs de concentration de poisson (DCP) artificiels dérivant (« dFADs ») (Maufroy et al. 2017). Les DCP artificiels ont été développés par la pêcherie à la senne

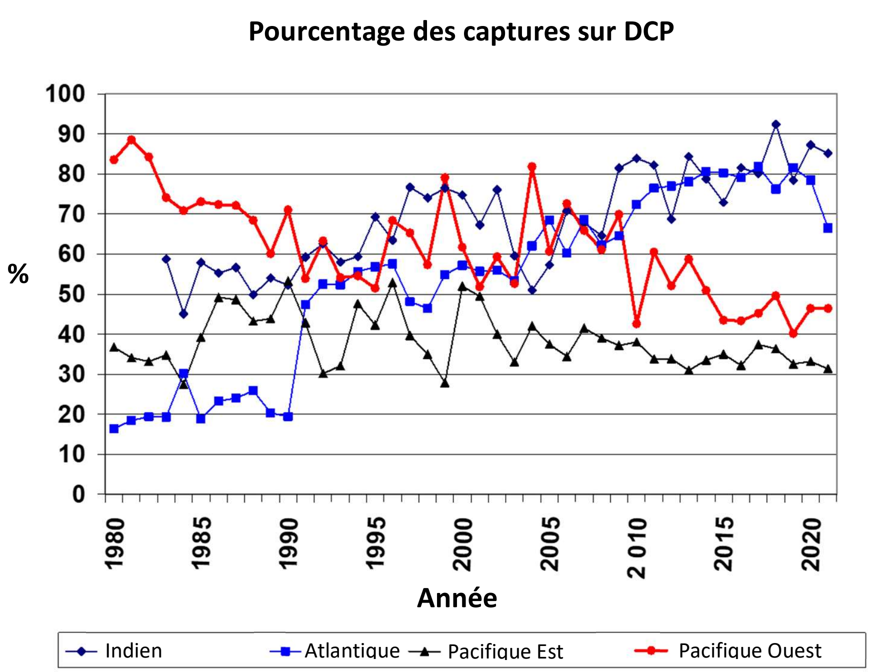


Figure 1.4: Historique du pourcentage des captures de thons majeurs faites sur dispositifs de concentration de poisson (DCP), par Océan. Source : Com. Pers. Alain Fonteneau

dans les années 1980 (Miyake et al. 2004; Majkowski 2007). Dans l'océan Atlantique et Indien, leur utilisation s'est intensifiée à partir des années 90's (Figure 1.4).

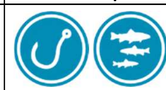
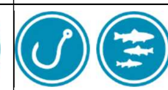
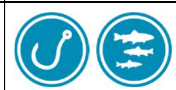
Ces radeaux sont accompagnés d'une balise GPS et, depuis les années 2015, d'échosondeur estimant la biomasse (masse, taille) en temps réel sous le radeau. « En 2020, 54.1% des captures à la senne provenaient de la pêche sous [objets flottants], 41% étaient issus de bancs libres et 4,5% venaient de bancs libres d'albacores associés à des dauphins, soit respectivement 36%, 27% et 3% des débarquements mondiaux de thons toutes techniques confondues.» Seret, Bach, and Dejouannet (2023). La pêche en banc libre cible les thons albacore alors que la pêche sur DCP cible les thons listao ainsi que les juvéniles d'albacore et de patudo. Il est intéressant de noter que les DCP ancrés sont généralement utilisés d'autres engins de pêche que la senne, notamment par les pêcheries côtières à canne des Maldives (Jauharee 2022). Dans cette thèse, nous feront référence à la pêche sur DCP (« FAD ») au sens structure de banc ciblé, regroupant donc les captures sur tous types d'objets flottants.

1.2.2. Etat des stocks de thons majeurs

En 2023, 9 stocks de thons tropicaux sur les 13 mondiaux sont considérés comme en bon état d'abondance (ISSF 2023). La surpêche (« overfishing stock ») correspond à un effort de pêche dépassant l'effort préconisé dans le cadre d'une gestion au Rendement Maximum Durable[8] (RMD) (F > Fmsy). Une situation de surpêche peut causer une situation de surexploitation du stock (« overfished stock ») correspondant à une biomasse de stock inférieure à la biomasse attendue à un effort de pêche au RDM (B < Bmsy) (Tableau 1.2). Dans l'océan Atlantique, seul le thon obèse est considéré comme surpêché (Fig. 1.5-b) mais non surexploité (ICCAT 2021). Dans l'océan Indien, le thon albacore et le thon obèse sont considérés surpêchés et surexploités (IOTC 2022a; 2022b).

[8] Le RDM de chaque stock est évalué de façon pluriannuelle lors d'évaluation de stock par les scientifiques.

Tableau 1.2: Caractérisation des trois espèces de thonidés tropicaux majeurs et état des stocks dans l'océan mondial (année d'évaluation). Les iconographies rouges signifient une surexploitation (poissons) ou surpêche (hameçon) avec Surexploitation : biomasse du stock < biomasse au RMD. Surpêche : effort de pêche > effort de pêche au RMD. Les iconographies bleues signifient une atteinte du RMD. Iconographies adaptées de la NOAA Fisheries.

Espèce (code FAO)	Nom français (Nom anglais)	Etat des stocks par océan		
		Pacifique	Indien	Atlantique
 *Katsuwonus pelamis (SKJ)*	Listao ou bonite à ventre rayé (Skipjack)	 2019	 2022	 2022
 *Thunnus albacares* (YFT)	Albacore (Yellowfin)	 2020	 2022	 2019
 *Thunnus obesus* (BET)	Patudo (Bigeye)	 2020	 2022	 2021

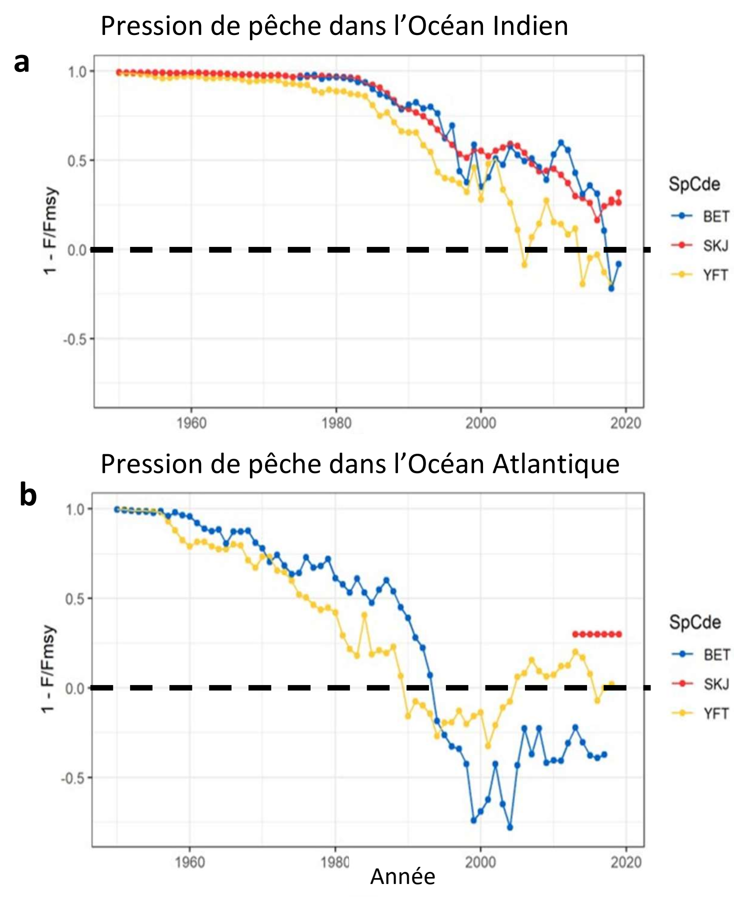


Figure 1.5: Evolution du rapport d'effort de pêche sur l'effort de pêche au RDM par espèce de thon tropical dans (a) l'océan Indien et (b) l'océan Atlantique, de 1959 à 2019. 1 correspond à un stock sans pression de pêche et 0 correspond à un stock pêché au RMD. SpCde correspond au code FAO pour chaque espèce : thon obèse (BET), thon listao (SKJ) et thon albacore (YFT). Données communiquées par le secrétariat de l'ICCAT et de l'IOTC. L'estimation de la pression de pêche historique pour le SKJ atlantique n'est pas encore disponible. Le Fmsy utilisé est spécifique à chaque espèce.

1.2.3. Historique et descriptif des captures des pêcheries thonières

Il existe actuellement cinq organisations régionales de gestion des pêches (ORGP) mandatées par les pays pêcheurs et des pays côtiers pour garantir la durabilité des ressources pélagiques, en particulier les thons, les espèces apparentées aux thons (*Scombridae*, *Istiophoridae* et *Xiphiidae*) et les requins pélagiques, relevant de leur compétence (Figure 1.6) : Commission internationale pour la conservation des thonidés de l'Atlantique (ICCAT) ; Commission des thons de l'océan Indien (IOTC) ; Commission pour la conservation du thon rouge du Sud (CCSBT) ; Commission des pêches du Pacifique occidental et central (WCPFC) ; Commission interaméricaine du thon tropical (IATTC).

Les captures de thonidés sont réalisées en grande majorité dans l'océan Pacifique où les captures sont en progression (Figure 1.7-A). Dans l'océan Atlantique, les captures totales de thons ont culminé à presque 800 000 tonnes dans les années 1980, mais sont en baisse depuis les années 1990 et atteignent aujourd'hui 600 000 tonnes par an, dominées par l'Espagne (entre 100 et 200 000 tonnes), suivie par la France (moins de 100 000 tonnes, Figure 1.7-B). La senne est, dans cet océan, l'engin de pêche assez largement dominant (55 % des captures totales). Dans les années 1980-1990, la diminution des rendements dans l'océan Atlantique a dans un premier temps incité les thoniers senneurs à explorer l'océan Indien comme nouvelle zone de pêche puis à se délocaliser, expliquant en partie la croissance importante des captures dans les années 1980 et 1990 dans l'océan Indien ainsi que la diminution concomitante de captures dans l'océan Atlantique (Marsac et al. 2014). Cette augmentation des captures de thons tropicaux dans l'océan Indien a été largement alimentée par l'Espagne et la France (utilisant principalement la senne), ainsi que par Taïwan et l'Indonésie (utilisant la palangre) (Figure 1.7-C). L'arrivée des thoniers senneurs dans l'océan Indien a fortement participé à l'augmentation de la capacité de pêche, conduisant à la surpêche des stocks d'Albacore et de thon Obèse (Figure 1.5-a).

En 2008-2009, une vague de piraterie somalienne dans l'océan Indien a eu des conséquences importantes sur la capacité de pêche, particulièrement des thoniers senneurs (ex. emploi d'une protection militaire à bord, pêche en couple, exploration de nouvelles zones de pêche) (Chassot et al. 2012), et s'est traduite par une diminution de plus de 40 % des captures totales (de 950 à 500 000 tonnes). Ces captures sont aujourd'hui en augmentation (à 650 000 tonnes), avec une légère dominance des senneurs, ciblant le listao et l'albacore, et des palangriers, ciblant le thon obèse et l'albacore (60 et 40 %, respectivement).

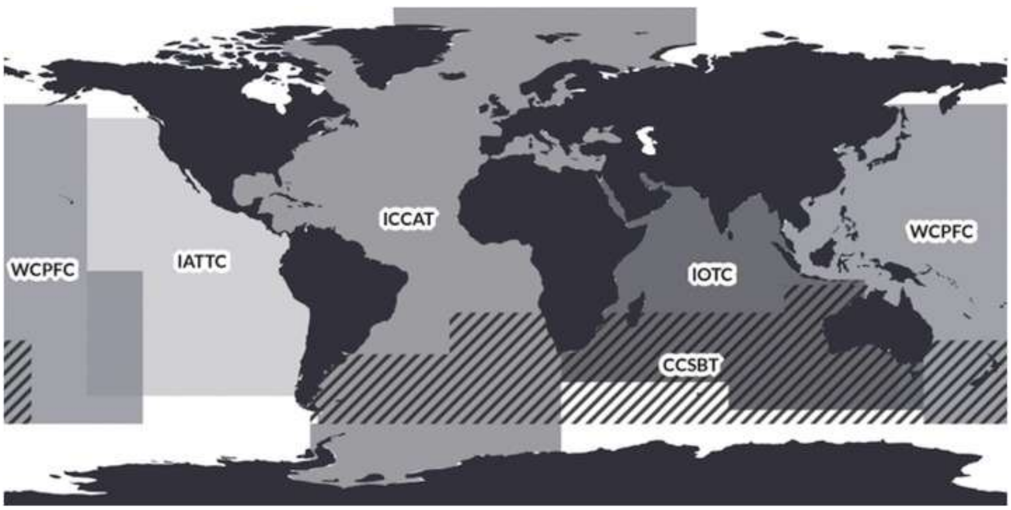


Figure 1.6: Domaines de responsabilité de chacune des organisations régionales de gestion des pêches (ORGP) de thonidés. ICCAT : Commission internationale pour la conservation des thonidés de l'Atlantique ; IOTC : Commission des thons de l'océan Indien ; CCSBT : Commission pour la conservation du thon rouge du Sud ; WCPFC : Commission des pêches du Pacifique occidental et central ; IATTC: Commission interaméricaine du thon tropical. Figure issue de Coulter et al., (2020)

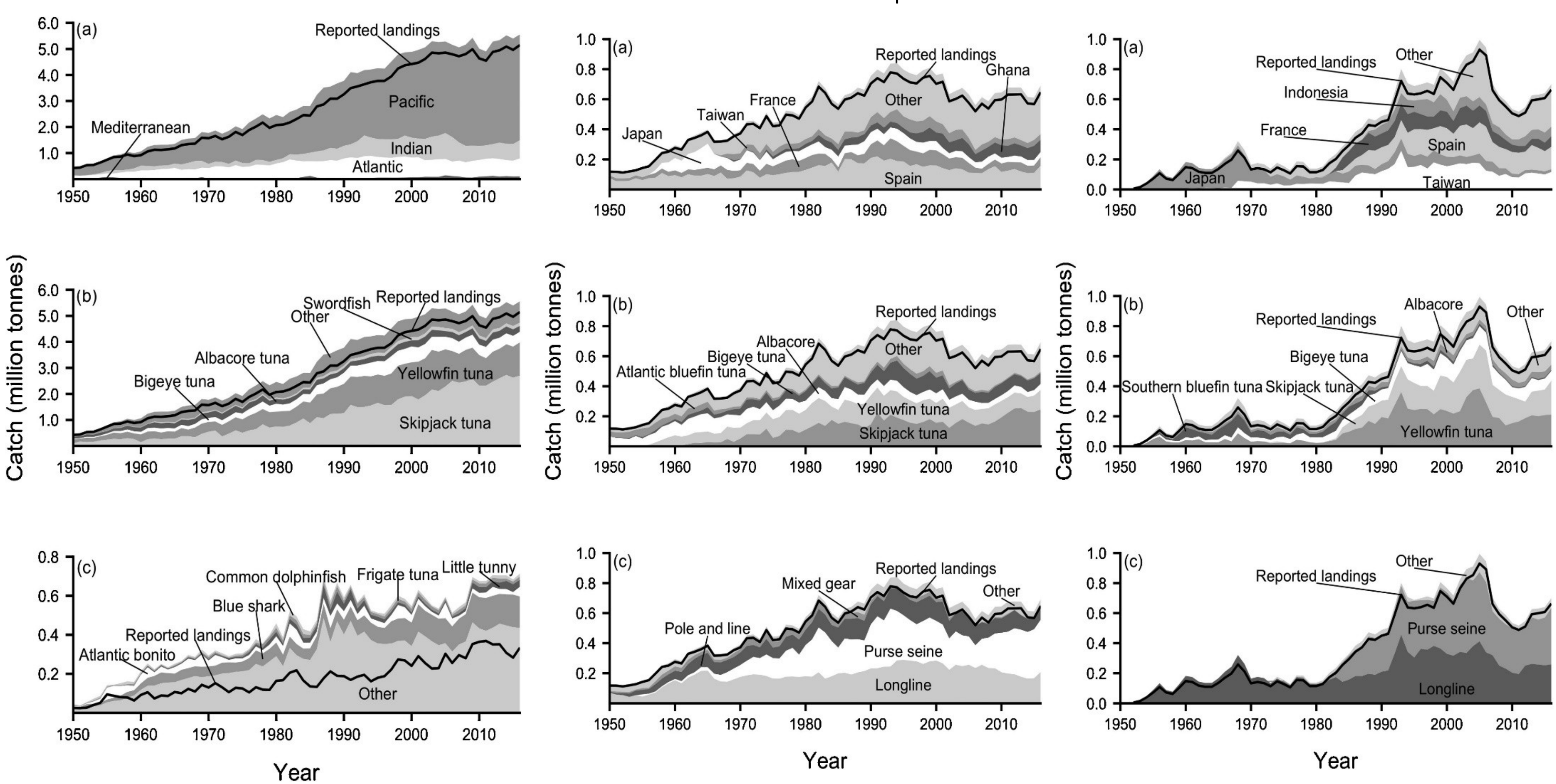


Figure 1.7: A- Prises mondiales de thons et d'autres grands poissons pélagiques de 1950 à 2016, assemblées et harmonisées à partir des cinq ensembles de données distincts des ORGP thonières, par A-a) bassins océaniques ; A-b) principaux taxons (156 taxons supplémentaires sont regroupés dans "Autres" (" Other") ; et A-c) taxons importants au-delà des 12 principales espèces cibles couvertes dans l'Atlas des captures de thons et de marlins de la FAO (144 taxons supplémentaires sont regroupés dans "Autres").

B- Captures de thons et de grands pélagiques dans l'océan Atlantique de 1950 à 2016, par B-a) pays de pêche (107 pays supplémentaires sont regroupés dans "Autres") ; B-b) taxon (134 taxons supplémentaires sont regroupés dans "Autres") ; et B-c) engin de pêche (9 catégories d'engins supplémentaires sont regroupées dans "Autres").

C- Captures de thons et de grands pélagiques dans l'océan Indien de 1950 à 2016, par C-a) pays de pêche (54 pays supplémentaires sont regroupés dans "Autres") ; C-b) taxon (83 taxons supplémentaires sont regroupés dans "Autres") ; et C-c) engin de pêche (5 catégories d'engins supplémentaires sont regroupées dans "Autres").

Figure adaptée de Coulter et al. (2020)

1.2.4. Interactions avec l'écosystème marin

En plus des espèces de thons majeurs, les pêcheries thonières interagissent avec de nombreuses autres espèces, et les capturent volontairement ou non alors appelées prises accessoires. Les prises accessoires peuvent être conservées à bord pour être valorisées (vendues ou consommés à bord), ou rejetées en mer. En volume, les prises accessoires sont principalement composées de thonidés mineurs et de requin peau bleu (*Prionace glauca*) (Figure 1.7-A-c). Le requin peau bleu, et plus généralement les requins et raies, sont des espèces accessoires pêchées principalement par les pêcheries palangrières (Worm et al. 2013 ; Gilman et al. 2011). Les pêcheries thonières industrielles[9] sont ainsi la principale menace pour les populations de requins pélagiques et de raies (Gilman 2011), ce qui est lié à la dynamique longue du cycle biologique de ces espèces (Dulvy et al. 2008). Toutes les ORGP, exceptée la CCSBT, disposent actuellement de mesures de gestion visant à réduire les prises accessoires de grands pélagiques non ciblés, notamment la mise en place d'observateur embarqués (BMIS 2024). Une forte proportion d'espèces accessoires (au sens espèces autres que thonidés majeurs) s'observe notamment dans l'Océan Atlantique de façon historique (Figure 1.7-B-b) comparé aux autres océans. Cela s'explique par une plus importante pêcherie artisanale dans l'océan Atlantique qui ciblent une plus grande diversité d'espèces en utilisant des engins mixtes[10] (Artetxe-Arrate et al. 2020), comparé à l'Océan Indien. Les captures des pêcheries artisanales sont toutes valorisées (vendues ou consommées). Il faut noter que cet écart avec l'océan Indien, comptant pourtant une plus grande proportion d'engins mixtes que l'océan Atlantique, relève d'une moindre qualité de la transmission des données à la CTOI (Figure 1.7-C) (Herrera et Pierre 2010).

1.2.5. Une diversité de pêcheries artisanales dans les Etats côtiers

Les flottes artisanales ne représentent qu'une petite partie des captures totales de chaque ORGP, à l'exception des pêcheries de la CTOI où les flottes semi-industrielles et artisanales

[9] Le terme artisanal et industriel se rapporte à des considérations socio-économiques sans de relation directe à la taille des navires (Cochrane and Garcia 2009 in FAO 2023). Dans cette thèse, on qualifie d'industriel l'ensemble des navires dont la taille dépasse 24 m de long. La pêche artisanale correspond à une taille de navire inférieure à 12 m car les 12-24 m sont plus souvent considérés comme semi-industriel. Définition personnelle.

[10] C'est-à-dire pratiquant plusieurs métiers de pêche

représentent environ la moitié des captures (Artetxe-Arrate et al. 2020; McCluney, Anderson, and Anderson 2019). Dans l'Océan Indien, la coexistence de flottilles artisanales (pêche à la ligne à main, à la ligne à traine, à la canne, à la palangre dérivante et filet maillant) et industrielles (senneurs, palangriers), pose un défi majeur pour l'évaluation et la gestion des stocks des thons tropicaux par la CTOI (McCluney et al. 2019; Murua et al. 2015) et plus largement dans le monde (Pons et al. 2023). Dans l'ensemble, la collecte des données des flottilles artisanales est moins coordonnée et naturellement plus difficile lorsqu'il s'agit de navires de petite taille. Les mesures de gestion sont plus difficiles à mettre en œuvre et à contrôler (Pons et al. 2017).

Les flottes artisanales et semi-industrielles des pays côtiers, originaires notamment de Libéria, Mauritanie, Nigeria Sierra Leone, Togo pour l'océan Atlantique et l'Inde, l'Indonésie, Oman, Yémen, Somali, Sri Lanka, Maldives pour l'océan Indien (Pauly et al. 2020), alimentent un marché local dont les bénéfices économiques et sociaux pour les territoires sont majeurs (taux d'emploi élevés, diversité d'utilisation des ressources et une valeur sociale pour les communautés côtières), mais cette pêche est en grande partie limitée aux zones côtières (Johnson 2018). Les flottes artisanales, dont les navires sont trop petits pour être soumis aux exigences internationales en matière de déclaration, débarquent au niveau national et n'ont qu'un accès limité au marché international des produits frais et congelés (Pons et al. 2023).

1.2.6. Caractéristiques du marché du thon en conserve

Le marché du thon est un marché international où près de la moitié des captures de thons sont échangées dans des chaines de valeur globalisées (46% en 2013 dans Lecomte et al. 2017). Les principales flottes qui alimentent ce marché sont les palangriers et senneurs industriels, qui se caractérisent par un haut niveau d'investissement (un thonier senneur neuf peut coûter une vingtaine de millions d'euros). Les senneurs ciblent les thons listao et albacore à destination du marché de la conserve alors que les palangriers ciblent des espèces de plus haute valeur, principalement le thon obèse et germon de grande taille (adultes), destinés au marché du sashimi (FAO 2022; Lecomte et al. 2017). A titre d'exemple, sur la période 2011-2012, le thon sashimi a atteint des prix 5 fois supérieurs aux prix du thon destiné aux conserveries (Guillotreau et al. 2017).

Le thon en conserve est le plus grand segment de marché en valeur (59.7 %), concentrant 76 % des captures mondiales de thon en 2014 (Macfadyen 2016). Le marché de la conserve est un marché de volume, qui produit donc à moindre coûts et est à la fois bon marché et facilement stockable pour le consommateur (García-del-Hoyo, Jiménez-Toribio, and García-Ordaz 2021). Par ailleurs, la conservation de ce prix faible est vue comme un enjeu pour la sécurité alimentaire (Schiller et al. 2018). La croissance de la demande est de l'ordre de 3% par an (Mullon et al. 2016). En effet, entre 1976 et 2011, le nombre de pays importateurs[11] a augmenté, passant de 5 en 1990 à plus de 200 aujourd'hui (données FAO). La demande de thon en conserve est inélastique[12] et donc peu sensible aux variations de prix (Lecomte et al. 2017). Cette demande inélastique traduit que la consommation de thon en conserve entre dans un type de consommation traditionnel. La demande des consommateurs finaux est plus inélastique au niveau des prix en Europe, mais l'est moins aux États-Unis. En revanche, le prix du thon du marché sashimi et du thon frais est élastique (Guillotreau et al. 2017)

Le prix du thon est aussi très volatile en raison de sa caractéristique mondialisée (Guillotreau et al. 2022). Le prix du thon a plus que triplé au cours des de la période 2000-2017. Dans le cadre de l'exploitation de ressources naturelles communes, on peut s'attendre qu'un prix de vente en conserverie soit influencé par la production (capture). Or, la demande de thon congelé des fabricants est considérée comme relativement élastique par rapport au prix mondialisé.

Ces propriétés du marché incitent les thoniers senneurs et leurs capitaines à adopter des stratégies de volumes plutôt que de qualité de capture (espèces ou de taille) (Schiller and Bailey 2021). Pour rester compétitifs, les armements investissent dans des navires plus grands pour augmenter leur capacité de pêche. Mullon et collaborateurs (2016), établissent une relation évidente entre la demande mondiale pour le thon et le niveau de captures des flottes, toute augmentation de la demande entrainant à une augmentation des captures terme. A plus

[11] Les états fédéraux des Etats-Unis ne comptent que pour un seul pays, contrairement aux Etats de l'Union Européenne.

[12] Si la quantité demandée diminue beaucoup avec l'augmentation du prix, on parle de demande très élastique ou très sensible au prix de vente.

long terme, l'augmentation de la demande mondiale entrainerait une augmentation des prix et des profits, qui conduirait à une augmentation de l'investissement dans les capacités de pêche, puis une augmentation de la pression de pêche qui causerait une rapide diminution des stocks, voire leur possible effondrement. La communauté scientifique estime que la mise en place de politique de régulation des captures ou de la puissance des navires par les ORGP thonières est nécessaire pour limiter l'investissement, la capacité de pêche induite et donc la pression sur les stocks de thon (Kaplan et al. 2014; Lecomte et al. 2017; Mullon et al. 2016).

1.3. La pecherie europeenne des thons tropicaux a la senne dans les oceans Atlantique et Indien comme cas d'etude

1.3.1. Structure économique des thoniers senneurs européens

L'efficacité de la pêche à la senne réside dans son fort rendement économique (volumes importants pour de faibles coûts d'exploitation). Les coûts principaux des senneurs sont les coûts liés au carburant et aux salaires (Figure 1.8). Au vu de l'importance des coûts de l'énergie pour cette pêcherie, le rendement économique est souvent réduit à l'efficience énergétique correspondant à la valeur ajoutée brute par litre de gasoil consommé. L'ensemble des coûts opérationnels (coûts variables, non variables, de réparation et de maintenance) souvent élevés sont compensés par des subventions, permettant aux pêcheries de thons de rester rentable (Lam et al. 2011 ; Sumaila et al. 2016).

L'utilisation croissante des DCP et leur développement technologique a permis aux thoniers senneurs européens d'augmenter leur efficacité de pêche (Dagorn et al. 2013; Maufroy et al. 2017). L'utilisation des DCP permet un meilleur rendement en moyenne (tonnage/coup de senne) car le nombre de coups de senne positifs (avec capture) est en moyenne deux fois supérieur à ceux de la pêche sur bancs libres (BL). Ces différents éléments font que la pêche sur DCP est considérée plus favorable économiquement que la pêche sur bancs libres.

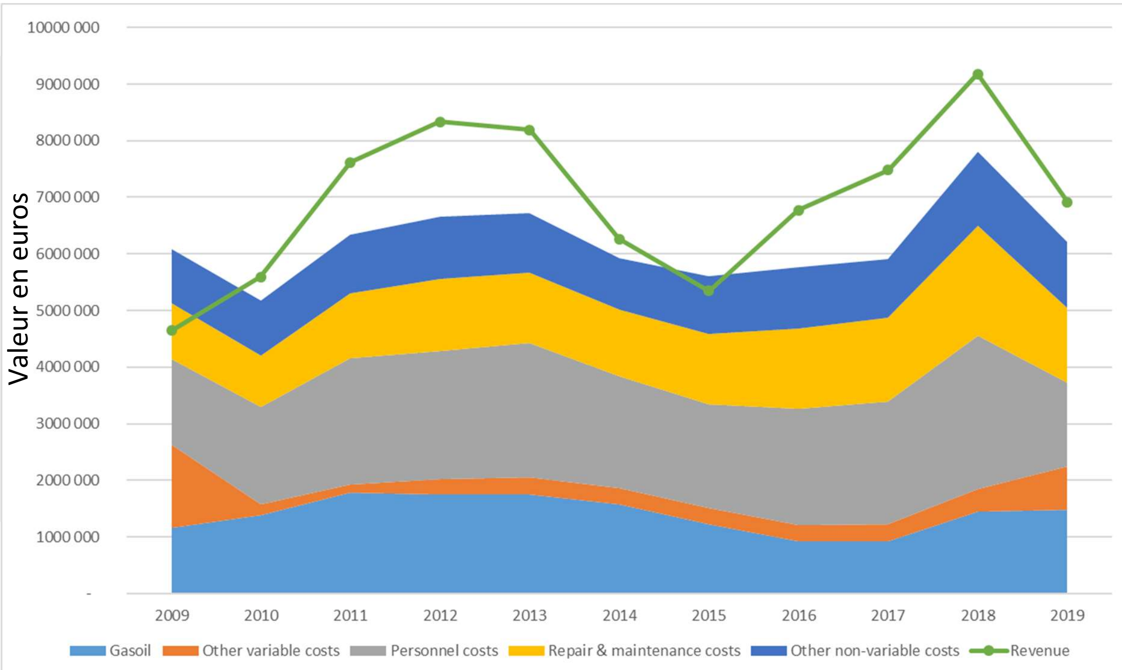


Figure 1.8: Structure des coûts moyens par thonier senneur français de 2009 à 2019. Source : Com.pers. Patrice Guillotreau - mis à jour avec les données de déclaration européennes (Annual Economic Report 21-08).

1.3.2. Problématiques liées à l'utilisation des dispositifs de concentration de poisson

L'utilisation des DCP induit des problématiques pour les différentes ORGPs, en raison de leurs conséquences sur l'environnement via plusieurs aspects :

(1) Les DCP augmentent la pression de pêche sur les juvéniles de thon albacore et de thon obèse, réduisant le rendement par recrue de ces espèces et ainsi participent à la surexploitation de ces stocks (Dagorn et al. 2013) ; (2) les DCP agrègent d'autres espèces que des thonidés, et pour certaines, des espèces de haut niveau trophique, dont la capture peut avoir de fortes conséquences pour l'écosystème pélagique (ex. requins, raies) (Juan-Jordá et al. 2018). Plus généralement la pêche sur DCP implique plus de captures accessoires et de rejets que la pêche sur bancs libres; (3) Les radeaux dérivants maillants peuvent induire de la

pêche fantôme (Filmalter et al. 2013); ainsi que (4) des déchets dans l'environnement marin avec des conséquences sur les espaces côtiers sensibles à l'abrasion (ex. coraux) (Imzilen et al. 2021; Maufroy et al. 2015; Zudaire et al. 2018) et causant de la pollution plastique (Moreno et al. 2023) ; (5) Le comportement des espèces pélagiques et des thonidés sous les DCP est encore mal connu. Sous l'hypothèse de thonidés persistant sous des DCP dérivant dans des habitats pélagiques moins favorables, ces derniers pourraient modifier leur habitats et augmenter la mortalité naturelle, agissant comme un piège écologique (Marsac et al. 2000; Dupaix et al. 2022).

D'un point de vue économique, la capture de jeunes adultes ou juvéniles de thons obèses sous DCP représente un coût d'opportunité important en termes de valeur perdue par les palangriers qui, eux, ciblent les thons obèses adultes (Guillotreau et al. 2017; Ovando et al. 2021). Les principaux outils de gestion envisagés et étudiés pour limiter la pêche sur DCP sont la création de fermetures spatio-temporelles à la pêche sur DCP ou d'aires marines protégées (ICCAT: Rec. 98-01, Rec. 96-13, Rec. 13-01; Perez et al., 2022), ainsi que des restrictions sur le nombre (ICCAT : Rec. 15-01 ; IOTC : Res. 15/08) et la zone de déploiement des DCP (Imzilen et al. 2021). Les ORGPs encouragent voire rendent obligatoire le développement et l'utilisation de DCP non emmêlant et biodégradable (Murua et al. (2021) ; ICCAT : Rec. 19-02, IOTC : Res. 17/08 ; 19/02) (Table 1.3).

Tableau 1.3 : Synthèse en anglais des réglementations de gestion des pêches, en particulier des pêcheries à la senne, mise en œuvre dans l'Océan Atlantique et l'Océan Indien par l'ICCAT et la CTOI respectivement

Subject	ICCAT – Atlantic Ocean		CTOI – Indian Ocean	
	Recommendations	First year of application	Resolutions	First year of application
Data call	. Rec. 1995-14: Catch and fishing effort data transmission . Rec. 96-13: Specific composition of landings . Rec. 13-01: FAD data on deployment, visit, position, etc. (FAD with echosounder) . Rec. 19-02: FAD data for all FAD (with and without echosounder)	.1968 .1997 .2014 .2020	.Res. 98/01: Catch, fishing effort and FAD deployed data transmission . Res. 10/02: More accurate data and landings size data . Res. 15/01: FAD data on deployment, visit, position, etc. . Res. 15/02: discard data in live weight and bycatch data . Socio-economic data call	.1999 .2011 .2016 .2016 .2018
Fishing effort	Moratorium (time-area closure) – . Rec 98-01 .Rec 11-01 .Rec 04-01 . Rec 15-01 . Rec. 19-02	.1999 .2005 .2012 .2017 .2020	. Res. 16/07: Prohibition of artificial surface or underwater lights to aggregate tuna . Res. 16/01: Catch limits for YFT (TAC) . Res. 18/01: Limits on supply vessel number	.2017 .2017 .2019
FAD use	. Rec. 15-01: Limit the number of FAD to 500 active beacons by vessel . Rec. 19-02: Non-entangling FAD	.2016-2018 .2021	. Res. 15/08: Limit the number of FAD to 550 active beacons by vessel . Res. 17/08: Biodegradable FAD . Res. 19/02: Non-entangling FAD	.2016 .2018 .2020
Bycatch	. Rec. 04-10: Transmission of sharks catch data . Rec 10-08: record the number of live and dead releases . Rec 19-01: Reinforced measures to conserve mako sharks	. 2004 . 2011 . 2020	. Res. 05/05: Transmission of sharks catch data . Res. 18/02: Protocol for the release of sea turtles	.2016 .2019
Discards	. Rec. 17-01: Prohibition of discards of tropical tunas caught by purse seiners	. 2018	. Res. 10/13: Prohibition of discards of tropical tunas caught by purse seiners	.2011
Observers program	. Rec. 10-10: on-board observer program (minimum coverage of 5%) . Rec. 19-02: on-board observer program (100% coverage of large-scale purse seiners)	.2011 .2020	. Res. 01/01 : on-board observer program . Res. 09/04: Observer coverage target of at least 5% of the number of operations for 2013 . Res 19/04: Enable the use of electronic monitoring to complement human observers	.2002 .2013 .2020
Stocks management	. Rec. 11-01: Multiannual conservation and management program for bigeye and yellowfin tuna . Rec. 14-01: Consideration of skipjack tuna in the management program	.2012 .2015	.Limiting the fishing capacity of bigeye tuna by reducing their fishing effort by 15% in 2002 compared to 1999 levels .Res. 18/03: establishes a list of vessels presumed to have carried out IUU fishing activities	.2002 .2019

1.3.3. Délimitation de l'étude : les flottilles de senneurs européens

Afin de réduire l'impact de la pêche sur l'environnement et la ressource, et de proposer une gestion intégrant les considérations écosystémiques et économiques, la flottille de pêche (groupe homogène de navire), voire le métier (groupe homogène d'activité), apparaît comme l'échelle la plus pertinente pour la gestion (Danto et al. 2021; Gascuel et al. 2012; Rybicki et al. 2020; Ulrich et al. 2012; 2007) et est devenue la référence pour la déclaration de données de pêche (Pauly, Zeller, and Palomares 2020; STECF 2017; Ye et al. 2017). Une flottille est un ensemble homogène de bateaux de pêche (même classe de taille) qui ciblent la/les même(s) espèce(s) sur une même zone avec le même engin de pêche et sous le même pavillon. Le métier correspond à la combinaison d'espèce(s) cible(s), le type d'engin, la(les) zone(s) de pêche ainsi que la période/saison de pêche et la durée de la marée. Un navire ou une flottille de pêche peut ainsi pratiquer différents métiers. Dans notre cas, on considérera que la pêche sur bancs libres et la pêche sur DCP constituent des métiers différents.

Les ORGP collectent les données halieutiques, notamment de captures et d'effort de pêche, à l'échelle des flottilles (ICCAT : Rec. 1995-14 ; IOTC : Res. 98/01). Dans cette thèse, le terme de flottille est défini par le pavillon, l'engin de pêche, l'océan. Les thoniers senneurs européens se réfèrent donc aux thoniers senneurs battant pavillon espagnol et ou français exploitant les thons tropicaux dans les océans Atlantique et Indien. Néanmoins, il faut noter que les entreprises de pêches (armements) qui les composent peuvent également posséder des navires qui font partie d'autres flottilles. Autrement dit, un armement français ou espagnol peut avoir des navires de pêche sous différents pavillons (Figure 1.9). Par exemple, une entreprise française travaillant dans l'océan Indien, peut avoir des navires sous pavillons français, mauricien ou seychellois. Les données de captures, d'effort de pêche, ou les données socio-économiques de la flottille française ne prendront en compte que les données issues des navires sous pavillon français. Or, les bateaux d'un autre pavillon participent aussi à la stratégie de pêche définie par l'armement et orientent donc la stratégie des bateaux sous pavillon national (ex. français). En particulier, l'effort de la flottille nationale dépend de l'utilisation commune de bateaux auxiliaires qui aident à la pêche ou du partage d'information entre capitaines sur leur stratégie, la localisation des bancs de thons, la position des balises GPS des DCP, etc. Ces éléments devront être pris en compte dans l'analyse des résultats.

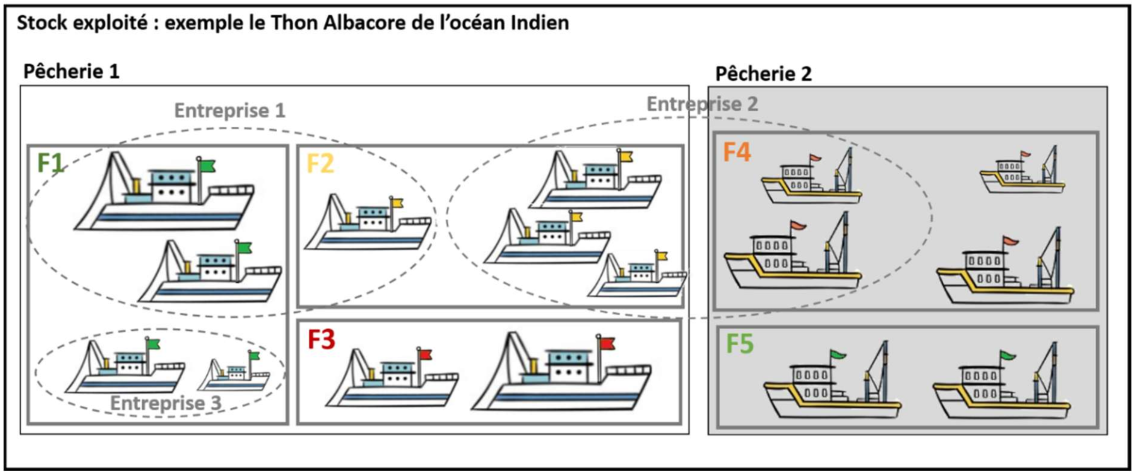


Figure 1.9: Schéma de définition des différentes unités de gestion employées. Stock : Espèce x Zone de pêche ; Pêcheries: stock x engin de pêche (schématisé par différent types de bateau) ; Flottille (F) : stock x engin de pêche x pavillon (schématisé par différents drapeaux ; L'entreprise de pêche peut se positionner dans différentes pêcheries voire différents stocks ; Un segment de flotte (schématisé par différentes tailles de navire) : Flottille x classe de taille.

1.4. Problematique et objectifs de la these

Compte tenu des éléments présentés précédemment sur les enjeux et les méthodes d'évaluation de la durabilité, et les problématiques des pêcheries thonières tropicales, la question générale qu'aborde ce travail de thèse est la suivante :

Quelles synergies peuvent-être construites entre les démarches d'évaluation multicritères de type tableau de bord d'indicateurs et analyse de cycle de vie, afin d'évaluer la performance de durabilité des pêcheries thonières tropicales dans la triple dimension écologique, économique et sociale ?

Elle se décline en plusieurs problématiques (1), (2) et (3), et qui se déclinant en question de recherche structurant les chapitres de la thèse.

(1) Dans quelles mesures les données actuellement collectées par les organismes de gestion des pêches permettent-elles d'évaluer l'ensemble des dimensions de la durabilité ?

<u>Question de recherche 1:</u> En l'état des connaissances et collectes de données disponibles sur les flottilles thonières, quels sont les critères qui peuvent être évalués et suivis dans un tableau de bord d'indicateurs de durabilité ?

Le **deuxième chapitre** répond à cette **1ère question** en proposant une méthode de construction d'un tableau de bord d'indicateurs de durabilité des pêcheries thonières, sur la base des données actuellement collectées par les organismes de gestion des pêches. Dans ce chapitre, l'accent a été mis sur l'approche méthodologique, avec l'objectif de proposer un tableau de bord pour l'ensemble des flottilles industrielles et artisanales sur la plus large période de temps disponible. Ce chapitre fait l'objet d'une publication scientifique sous la forme d'un « data paper » intitulé « A multidimensional dashboard of fishery sustainability indicators, using tropical tuna fishing fleets as a case study» en cours de soumission dans le journal *Ecological Solutions and Evidence*.

(2) Les deux approches, tableau de bord et analyse de cycle de vie, permettent-elles un suivi temporel des performances de durabilité ? Et dans quelles mesures ces indicateurs informent-ils sur la dynamique de la durabilité des pêches ?

<u>Question de recherche 2 :</u> Que nous enseigne un tableau de bord d'indicateurs sur la durabilité des flottilles thonières ? Dans quelles mesures ces flottilles sont-elles durables au regard des critères pris en compte ? Est-il possible de les comparer et de suivre dans le temps leurs performances de durabilité ?

Le **troisième chapitre** répond à cette **2ème question** et reprend en partie les résultats du tableau de bord d'indicateurs et analyse la coévolution des indicateurs de durabilité, afin de mieux comprendre les liens entre dimensions écologiques, économiques et sociales. Ce chapitre discute des performances de durabilité des flottilles thonières entre elles et au cours du temps. A la lumière des manques éventuels du tableau de bord, ce chapitre discute également de propositions de gestion pour les pêcheries thonières à la senne, notamment en termes de données collectées et d'utilisation de ces données pour informer la gestion. Ce chapitre fait l'objet d'une publication scientifique intitulée « When economy meets ecology, is it truly conflicted? A dashboard approach to assess the sustainability performance of European tropical tuna purse seine fisheries » accepté et en cours d'impression dans le journal *Science of the Total Environment*.

Question de recherche 3 : Dans quelles mesures l'analyse de cycle de vie informe sur les différences d'impact des flottilles thonières tropicales européennes à la senne et de leurs stratégies de pêche (DCP versus bancs libres) ainsi que leur impact au cours du temps ?

Le **quatrième chapitre** répond à cette **3ème question** et utilise l'approche d'analyse de cycle de vie pour caractériser et suivre les performances de flottilles thonières européennes à la senne afin de mieux caractériser les impacts relatifs de cette activité de pêche. Il permet de compléter l'appréciation qui a pu être faite par le tableau de bord, notamment la différentiation des impacts environnementaux entre les différentes stratégies de pêche sur banc libre et sur dispositif de concentration de poisson. Ce chapitre fera l'objet d'une publication scientifique après sélection des résultats, relecture et correction par les co-auteurs impliqués. Ce chapitre est intitulé à ce jour: « For a more sustainable tropical tuna, fishing strategy and fishing fleet matters. A life cycle assessment approach».

(3) Quelle est la complémentarité entre les deux approches d'évaluation multicritère de la durabilité d'une activité de pêche : tableau de bord d'indicateurs et l'analyse de cycle de vie ?

Question de recherche 4 : Dans quelles mesures les deux approches, tableau de bord d'indicateurs et analyse de cycle de vie sont-elles redondantes ou complémentaires ?

Question de recherche 5 : Quels sont les facteurs principaux de la durabilité des flottilles thonières ? Quelle applicabilité des outils multi-critères pour les ORGPs ? Peut-on identifier des leviers d'amélioration pour leur gestion ?

Le **cinquième chapitre** est une discussion générale de la thèse qui revient sur les principales conclusions sur les performances de durabilité des flottilles thonières européennes à la senne. Ces performances sont discutées au regard de la littérature et des limites de ce travail. Les complémentarités ou redondances trouvées entre l'approche tableau de bord et ACV ainsi que les leviers d'amélioration de la gestion sont établis. La pertinence des deux approches est discutée pour d'autres flottilles ou cas d'études, ainsi que pour la filière pêche plus généralement. Ce chapitre expose ce qui doit être retenu de ce travail pour servir la gestion. Il propose des perspectives de recherche pour mieux répondre aux enjeux de durabilité de la filière et de la pêche.

1.5. Références du chapitre 1

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2. UN TABLEAU DE BORD D'INDICATEURS MULTIDIMENSIONNEL DE LA DURABILITE DES PECHERIES. CAS D'ÉTUDE DES FLOTTILLES THONIÈRES TROPICALES

A multidimensional dashboard of fishery sustainability indicators, using tropical tuna fishing fleets as a case study

Article à soumettre

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indicators, ecological impact, socio-economic, fisheries, RFMO, STECF, Atlantic Ocean, Indian Ocean, multicriteria

Abstract

A holistic sustainability assessment of fisheries is necessary to understand how fisheries are achieving the sustainable development goals set by the UN. Using a data-rich case study (Atlantic and Indian tropical tuna fisheries), we present a fisheries' sustainability performance dashboard that gathers 24 indicators (13 ecological, 7 economic, 1 technic and 3 social indicators). Ecological

and technic indicators were calculated from 1950 to 2022 for 346 fleets (145 flags, 7 fishing gears, 2 vessel-size scales, 34 sub-fishing gears, 2 oceans), while the economic and social indicators were calculated for 54 European fishing fleets from 2009 to 2022 (5 fishing flags, 6 fishing gears, 6 vessel-size scales, 2 oceans). A statistically validated approach based on the fishing effort allocation is used to disaggregate economic and socio-economic public data, geographically and by vessel-size scale. The final dashboard is a tool to monitor the sustainability performance and compare tropical tuna fishery performances between flags, fishing gears, periods or vessel-size scale. We highlighted the lack of social data. The dashboard can be consulted online (Shiny application) and is available to download.

DATASET: The dashboard and the associated R code are available to download on the following repository: https://entrepot.recherche.data.gouv.fr/dataverse/root?q=DECOD (Data identification number: https://doi.org/10.57745/Z0PH0Q).

2.1. SUMMARY

In the context of both global overfishing and growing population demand for marine seafood, a comprehensive approach to the sustainability assessment of fisheries is ad-vised. The fisheries 'sustainability definition could cover different dimensions, e.g. eco-logical, economic, social, governance, climate change vulnerability, fish welfare and nutrition (Anderson et al. 2015; Danto et al. 2021; McCluney, Anderson, and Anderson 2019). Recent developments in the technology, available to collect, manage and ana-lyse fishery-relevant data, are an opportunity to monitor the sustainability of fisheries (Bradley et al. 2019). However, an application of a holistic approach allowing monitoring of the multidimensional sustainability of fishing fleets was never conducted, and the capacity of collected fisheries data to monitor fisheries sustainability is still unknown (McCluney, Anderson, and Anderson 2019; Drouineau et al. 2023; Gascuel et al. 2021). To assess such performances, a dashboard of indicators at a fishing fleet scale is recommended (Drouineau et al. 2023; Capello et al. 2023). A fishing fleet is composed of vessels with similar vessel sizes, fishing gear, fishing areas, and target species under the same national flag (Parsa et al., 2020;

Ulrich et al., 2012). A fishing fleet could have different fishing métier, i.e., similar fishing practices (Parsa et al., 2020).

The paper presents a multidimensional dashboard built based on the state-of-the-art sustainability indicators of relevant fisheries and the availability of tropical tuna fisheries data. We use the tropical tuna fisheries in the Atlantic and Indian oceans as a data-rich case study to understand which sustainability indicators can be monitored using historical fisheries data reporting. Tropical tuna fisheries are a significant fishing activity worldwide, representing 7% of the volume of global marine landings in 2022, respectively (FAO, 2024). Atlantic and Indian tropical tuna fisheries account for over 38% of global major tuna catches in 2022 (FAO 2024). The fishing gears used by tropical tuna fisheries are purse seine, longline, gillnet and pole and line for industrial fisheries and pole and line, longline and gillnet for artisanal fisheries (McCluney, Anderson, and Anderson 2019).

Available public updated data on tropical tuna fisheries activities (e.g., specific catches, landings, bycatch, discards) are provided by tuna Regional Fisheries Manage-ment Organizations (RFMOs). RFMOs don't collect socio-economic data. We used Euro-pean socio-economic data from the Data Collection Framework (DCF) of the European Union (Regulation EC 199/2008) for European tropical tuna fisheries, e.g., data on fisheries variable costs and non-variables costs, salary, number of employees, fuel consumption, and value at landing.

We developed a method to increase the scale of these data. Public socio-economic data on European tropical tuna fisheries are available for vessels gathered by vessel size (statistical individuals: flag*gear*vessel-size*year). However, data are only available for the global ocean (geographical aggregation). Also, data are aggregated and declared for larger vessel sizes for specific years and fleets. Thus, the socio-economic data of one fleet cannot be compared between years. Twenty-five percent of tropical tuna fishing fleets' da-ta are aggregated, making data not adapted to monitor the socio-economic performance of these fleets in a robust way (Quemper et al. 2024). A combined geographical and vessel-size disaggregation method based on fishing effort allocation is proposed. Our statistically validated approach could be applied to other geographical and vessel-size aggregated fleets.

The tropical tuna fisheries' sustainability performance dashboard gathers 24 indicators (13 ecological, 7 economic, 1 technic and 3 social indicators). Ecological indicators were calculated from 1950 to 2022 for 346 fleets (143 flags , 7 fishing gears, 2 vessel-size scales, 36 sub-fishing gears, 2 oceans), while the economic and social indicators were calculated for 54 European fisheries from 2009 to 2021 (5 fishing flags, 5 fishing gears, 6 vessel-size scales, 2 oceans). This dashboard data has been used in published research on the sustainability performance comparison between European tropical tuna purse seine fisheries (Ougier et al. 2024). The present dashboard can support further ecological sustainability performance comparison between tropical tuna fishing fleets, e.g. by fishing gears and vessel-size scale). Here, we present the dashboard by several indicators and fishing fleets available over time by indicator categories (i.e. ecological, technic, economic, social) and decennia. The dashboard can be consulted online (Shiny application) and is available to download.

This work highlights that assessing the socio-economic sustainability of tropical tuna fisheries remains challenging as tuna RFMOs don't wonder about socio-economic data from their fishing member states. For now, research on socio-economic fishery performance is case study-specific. Thus, the data collected for tropical tuna fisheries remain not adapted to assess and monitor the sustainability performances between fishing fleets (da-ta collection missing, e.g., vessel fuel, material consumption, socio-economic data) (Basurko et al. 2023; Chassot et al. 2021; Dueri et al. 2016; Murillas-Maza, Moreno, and Murua 2013). This work answers this challenge for European tropical tuna fisheries in the Atlantic and Indian oceans (36 fishing fleets, including French and Spanish purse seine fleets).

2.2. DATA DESCRIPTION

The dashboard of sustainability performance indicators is composed of two datasets for homogeneity with the original public data format used (i.e. from the RFMOs in one part and from the European Union in another part):

. Ecological and technical indicators dataset (from RFMOs' public data): A first dataset of 6,588 lines and 22 columns (9 columns for fleets) with all ecological indicators except two (FUI and carbon footprint), one technical indicator and one economic indicator (inter-annual variability of catch) for 346 fleets (i.e. flag*fishing gear* fishery type) in the Atlantic and Indian oceans and from 1950 to 2022 (Table 2.2) was produced.

. Economic, socio-economic and ecological indicators dataset (from public European Union's data): A second dataset of 520 lines and 62 columns, i.e. ten columns of fleet characteristics (Table 4), thirty-five columns of desegregated STECF technic, economic and socio-economic data and associated socio-economic indicators (Table 2.3), four columns of economic environment variables (gasoil price, barrel price, SKJ and YFT price), and two columns of ecological indicators (FUI and carbon footprint). This dataset contains indicators for 36 European fleets (5 fishing flags, 5 fishing gears, 6 vessel-size scales) in the Atlantic and Indian oceans for the 2009 – 2022 period.

The dashboard can be consulted and explored online: http://halieut.agrocampus-ouest.fr/discardless_app/acv_dashboard/.

The dashboard, corresponding to the two datasets, the list of raw data used, their version and public link as also the associated R code are available to download on the following repository: https://entrepot.recherche.data.gouv.fr/dataverse/root?q=DECOD (Data identification number: https://doi.org/10.57745/Z0PH0Q).

Tidy data principles are used to structure data frames (Wickham 2014) and FAIR data principles were included in describing the published open data (Wilkinson et al. 2016). The repository "Recherche Data Gouv", providing a permanent digital online identifier (DOI) and a streamlined update of data, was retained. For ecological indicators, fishing fleets are defined by the following variables: flag, fishing gear, ocean basin, and vessel size category (artisanal or industrial, as defined in RFMOs' databases). For economic and social indicators, fishing fleets were defined with the following variables: flag, fishing gear, ocean, and vessel size segment. The year listed is the date of fish production (catches) by the fishing fleets.

2.3. Materials and methods

2.3.1. Selection of the dashboard indicators

The dashboard of indicators is constructed to i) evaluate its application on all tropical tuna fisheries and ii) compare tropical tuna fishing fleets' sustainability performances with the European purse seiners in the Atlantic and Indian Oceans as case-study (Ougier et al. 2024). A set of 24 candidates' indicators is identified from (1) the peer-reviewed literature on theoretical multi-dimensional dashboards already supported by case studies: the RAPFISH technique (Pitcher and Preikshot 2001), the Fishery Performance Indicators method (Anderson et al. 2015), the VALDUVIS tool (Kinds et al. 2016), (2) the peer-reviewed literature on tuna fisheries specific ecological indicators (Chassot et al. 2021; Juan-Jordá et al. 2018; Parker et al. 2018; Schaefer 1954) and (3) technical reports on sustainable fishing indicators co-developed with the French fishing industry (Danto et al. 2021; Dewals and Gascuel 2020) (Sup. Table 2.1). From the list of 111 candidate indicators, twenty-four have been selected, according to the following rationales: the scale of the indicator information is suited to assess the sustainability at the fleet level, the public data are available or easy to obtain at the year level (Sup. Table 2.2).

The resulting dashboard covers the following aspects: the status of targeted stocks, the ecological footprint of fleets on targeted stocks and the marine ecosystem, the fishing mode used, the temporal trend of tuna catches, economic health, and ecological efficiency of energy (i.e. economic productivity, fuel use intensity), employment stability and average wage levels. These aspects are organised by sustainability dimension (i.e. the border system considered). Each dimension is defined by a criteria i.e, a rationale of why this is important for fishery sustainability. For each criteria, a numerical indicator is constructed to determine whether the criteria are respected. A higher indicator results in a higher sustainability performance. Of the 111 candidate indicators, we are able to calculate twenty-four (23%) (Table 2.1). It should be highlighted that this dashboard of indicators doesn't inform on the overall fishery sustainability dimensions but on those that can be easily monitored nowadays. Thus, this list of indicators results from our capacity to monitor fishery sustainability and should be considered a first research result.

Tableau 2.1: Synthetic table of indicators calculated and how they should be interpreted. Indicators equations are available in Sup. Mat. 1.2.

Dimension	Indicator name	Criteria	Interpretation aid	Public data sources
Biological & Ecological system	Stock assessment reliability	The fleet is exploiting fishing stocks based on reliable stock assessment	The higher the score, the more the fleet is exploiting a stock whose stock assessment quality is good i.e., low uncertainty.	RFMOs: - International Commission for the Conservation of Atlantic Tunas (ICCAT) - Indian Ocean Tuna Commission (IOTC) (I.e. Catch, fishing effort, biomass, catch size)
	Overfishing stock	The fleet is exploiting fishing stocks that are not subject to overfishing	The higher the score, the more the tuna stocks, targeted by the fleet, in proportion to catch, is preserved from overfishing.	
	Stock biomass (relatively to Bmsy)	Tuna stock biomass is not overfished relative to MSY	The higher the score, the more the tuna stocks, targeted by the fleet, have large biomass relative to Bmsy	
	Spawning stock biomass (relatively to SSBmsy)	Tuna stock spawning biomass is not overfished relative to MSY	The higher the score, the more the tuna stocks, targeted by the fleet, have large spawning biomass relative to SSBmsy	
	Stock biomass (relative to B0)	Participation capacity of biomass of exploited stocks in the ecosystem in a pristine state (without fishing)	The higher the score, the more the fleet is exploiting stocks whose biomass is close to the virgin state and thus available for the functioning of the ecosystem	
	Spawning stock biomass (relative to SSB0)	Participation capacity of spawning biomass of exploited stocks in the ecosystem in a pristine state (without fishing) - Protection of juveniles	The higher the score, the more the fleet is exploiting stocks whose spawning biomass is close to the virgin state and is available for the functioning of the ecosystem	
	Mature catch rate	Exploitation diagram is consistent with protection of juveniles	The higher the score, the more the fleet is exploiting mature fish, thus limiting its impact on stocks recovery (Tuna length L > L with 50% of maturity)	
	Species-based selectivity	The fishery is selective and impacts only the target species	The higher the score, the more the fleet is selective and fewer non-targeted species are impacted	
	Discard rate	The fishery does not waste biomass	The higher the score, the lesser the fleet is discarding biomass and the lesser the ecosystem impact	
	Sensitive species catch rate	Minimum impact on the least productive biomass (sensitive species)	The higher the score, the lesser the fleet's catch of conservation-status species (sharks, turtles) and the lesser the ecosystem impact	
	Bycatch TL mean	Bycatch and discards concern species of low trophic level	The higher the score, the lesser the fleet is impacting high trophic levels in the ecosystem	
	Fuel use intensity	The fuel use intensity is less by landings in weight	The higher the score, the lesser the fleet is consuming fuel by kilo caught, and thus has a potential impact on climate change	European Union: STECF (Annual Economic Report)

	Carbon footprint	The carbon footprint is less by landings in weight	The higher the score, the lesser the fleet emits the most CO2 by kilo caught and thus has a potential impact on climate change	(I.e. fuel consumption in liters)
Technical system	FSC fishing rate	The catch rate on FSC is sufficiently important not to impact the resource or ecosystems	The higher the score, the lesser the fleet may have an impact on stocks, bycatch and sensitive species, and thus on the ecosystem	RFMO data source
Economic & Finance system	Variability in catch	Tuna catch is stable: inter-annual variability of tuna catch is low	The higher the score, the lesser the significant tuna catch changes from one year to another	European Union: - STECF (Annual Economic Report) (I.e. economic and socio-economic variables data, landings in weight and value) (I.e. tuna price (Campling, Havice, and McCoy 2022))
	Importance of non-renewable energy costs	The non-renewable energetic dependence is low	The higher the score, the lower the non-renewable energetic dependence of the fleet (Lowest non-renewable energy costs relative to the turnover).	
	Energy efficiency	The economic productivity of energy is good	The higher the score, the higher the economic productivity of energy of the fleet (Greatest gross added value relative to the fuel consumption)	
	Margin rate	The economic profitability is good	The higher the score, the higher the economic productivity of the fleet (Highest gross operating profit relative to the gross added value)	
	Net profit	The economic profitability is good	The higher the score, the higher the economic productivity of the fleet (Highest landing incomes with lowest total costs)	
	RoFTA	Productivity of the capital is good	The higher the score, the higher the return of tangible assets (RoFTA) of the fleet (Highest gross operating profits relative to physical capital values)	
	Variability in YFT's prices	Tuna price is stable: inter-annual variability of tuna price is low	The higher the score, the lesser significant yellowfin tuna price changes from one year to another	
Socio-economic system	Work productivity	The work productivity is good	The higher the score, the higher the work productivity of the fleet (Highest gross added value relative to the number of full-time equivalents)	
	Created FTE	Employment is stable across successive year	The higher the score, the greater the number of jobs created (in full-time equivalent – FTE) from one year to another. It is not the absolute number of FTE.	
	Average personnel costs	Salary levels are good	The higher the score, the higher the average personnel costs and higher the average salary (Greatest salary costs regarding the number of full-time equivalents)	

2.3.2. Public data collection and cleaning of tuna RFMO datasets

The public data used for the dashboard construction are controlled and archived by two tuna RFMOs, the International Commission for the Conservation of Atlantic Tunas (ICCAT) and the Indian Ocean Tuna Commission (IOTC) in the Atlantic and Indian Oceans. It corresponds to mandatory fishery data provided yearly by fishing countries. Data for Task 1 (capture by species and by gear) and Task 2 (georeferenced catch and fishing effort by species and by gear) can be downloaded directly from RFMOs websites (ICCAT - www.iccat.int ; IOTC – www.iotc.org).

From ICCAT and IOTC data, a common catch data frame for both oceans is created to retain the catches, landings, and discards by species for each tuna fishing fleet (for more details on the code, see Dashboard construction.pdf). Discard data were only available for the Indian ocean. To focus on tuna tropical fisheries, fishing fleets in the fishing areas East-Tropical and West-Tropical in the Atlantic Ocean and in the fishing FAO areas 51 and 57 in the Indian Ocean are selected. Fishing fleets targeting Mediteranean stocks were removed. The raw public data used for the dashboard construction are available in the file “ICCAT IOTC and STECF raw data” in the repository. The source and the version of each raw data are available in the “Read_me” Excel file.

Tuna fishing fleets analysed were composed of industrial (over 24m), semi-industrial (12 to 24m) and artisanal (<12m) vessels using one fishing gear like purse seine, longline, pole and line or gillnet (McCluney, Anderson, and Anderson 2019). Other fishing gear not targeting tropical tunas are removed, i.e. trawlers. The IOTC only provides a fleet classification by vessel size category (industrial versus artisanal fisheries). For Atlantic fleets, we assumed that only coastal fishing member states have artisanal fisheries. They are Benin, Cameroon, Republic of Congo, Curacao, Equatorial Guinea, Gabon, Ghana, Guinea, Guinea Bissau, Ivory Coast, Liberia, Mauritania, Nigeria, Senegal, Sierra Leone and Togo. We assumed that catches reported by those coastal countries come from their artisanal fishing fleets.

Based on the formatting and filtering RFMOs data, the number of tuna fishing fleets (flag*gear*vessel size) considered was 185 for the Atlantic Ocean and 115 for the Indian Ocean (Table 2.2).

Historical data of biomass indicator estimates for the major tropical tuna species (i.e., stock biomass, spawning biomass, biomass at maximum sustainable yield (MSY), and spawning biomass at MSY) arose from fish stock assessment outputs and is provided on demand by RFMO secretariats. Data on fishing efforts was available from the ICCAT and the IOTC website. Stock status parameters (fishing mortality at MSY, confidence interval around fishing mortality of the stock assessment estimations, size at 1st maturity) corresponded to the most recent stock assessment for the three major tropical tunas (Katsuwonus pelamis – SKJ, Thunnus albacares – YFT, Thunnus obesus - BET) performed by RFMOs (SKJ: (ICCAT (2022), IOTC (2017c); YFT: ICCAT (2019), IOTC (2017); BET: ICCAT (2018), IOTC (2017b)).

The technical and the majority of ecological indicators of the dashboard are calculated by fleet (flag, fishing gear, vessel size), by the ocean (Atlantic and Indian oceans), and by year (1950-2022) (Table 2.2), providing a first matrix of 6,588 lines and twenty-two columns (nine columns being fleet characteristics). For each fleet, eleven ecological fishery-based indicators are calculated (stock assessment reliability, overfishing stocks, stock biomass (relatively to Bmsy), spawning stock biomass (relatively to SSBmsy), mature catch rate, stock biomass (relatively to B0), stock biomass (relatively to B0), species-based selectivity, discard rate, sensitive species catches, bycatch trophic level mean), one technical indicator (Free School -FSC- fishing rate in number of sets) and one economic indicator (variability in catch). Details of the calculation method of all indicators with R code are provided in Supplementary Material 1.2.

*Tableau 2.2 : Amount of tropical tuna fishing fleets (flag * fishing gear group* vessel size category) present in the first dashboard dataset (Ecological and technical indicators).*

Fleet characteristics		Atlantic Ocean	Indian Ocean
Fishing Gear Group	Purse seine	56	16
	Longline	57	65
	Baitboat	41	37
	Gillnet	13	26
	Troll line	13	0
	Other	16	1
	Unknown	21	0
Vessel size category	Artisanal	22	67
	Industrial	177	72
	Unknown	12	6
The total of different fishing fleets		185	115

With fishing gear groups corresponding to the following fishing gears:
. Purse seine (PS): PS double-boat, PS large scale, PS medium scale, small PS;
. Baitboat – (BB): BB freezer, BB ice-well, BB mechanized, BB non-mechanized, BB offshore, hand line, hand line offshore;
. Longline – (LL): LL targeting swordfish, LL fresh, LL operated attached to gillnet, LL bottom and deep longliners, drifting LL, surface LL, costal LL, LL foreign-based, LL home-based, LL with mother boat, LL targeting sharks;
. Gillnet – (GL): fishnet, GL offshore, GL operated attached to longliners;
. Troll: troll line, trolling mechanized, trolling non-mechanized;
. Other: Ring net offshore, other surface, trap, trawl, trawl mid-water pelagic, all gears.

2.3.3. Public data collection and data cleaning of European Union datasets

The Scientific, Technical, and Economic Committee for Fisheries (STECF) of the European Union provided data for economic and socio-economic variables of European fisheries, including European tropical tuna fisheries. Data on the fleet segment resolution is downloaded (STECF 20-06 - EU Fleet Economic and Transversal data_fleet segment.xlsx) from the STECF website (https://stecf.jrc.ec.europa.eu/reports/economic). The STECF website provides also landing data in weight and value by FAO areas, species and fleets ("STECF 20-06 - Landings_all_fao.csv") with a similar fleet resolution of the economic and social dataset (flag*gear*vessel-size*year). Six different fleet segments (vessel-size categories) are available: <10m, 10m-12m, 12m-<18m, 18m-<24m, 24m-40m and >40m. Table 2.3 presents the available economic and socio-economic variables. However, this does not mean that a value is available for each variable; for example, unpaid labour remains an empty variable for most fisheries. Socio-economic variables presented in Table 3 are called social variables because they are part of fisheries sustainability's social dimension. Data are complete for the period 2009–2019. Several variables, like unpaid labour, quota rental income, license costs, subsidies, and debts, cannot be used for indicator calculations due to the low level of fleet data reporting.

Tableau 2.3 : Available and filled-in variables in the STECF data and corresponding variable codes. GT: Gross tonnage. kW: kilowatt. LOA: Length overall. FTE: Full Time Equivalent

Type of variables	Variable name	Variable code
Fishing effort variables	Days at sea	totseadays
	Fishing days	totfishdays
	GT days at sea	gtseadays
	GT fishing days	totgtfishdays
	kW days at sea	kwseadays
	kW fishing days	totkwfishdays
	Maximum days at sea	maxseadays
	Number of fishing trips	tottrips
Capacity variables	Total vessel power	totkw
	Total vessel tonnage	totgt
Technic variables	Mean age of vessels	avgage
	Mean LOA of vessels	avgloa
	Number of vessels	totves
Economic variables	Consumption of fixed capital	totdepcost
	Energy consumption	totenercons
	Energy costs	totenercost
	Gross debt	debts
	Value of physical capital	totdeprep
	Gross value of landings	totlandginc
	Income from leasing out quota	totrightsinc
	Investments	totinvest
	Lease/rental payments for quota	totrightscost
	Operating subsidies	totdirsub
	Other income	tototherinc
	Other non-variable costs	totnovarcost
	Other variable costs	totvarcost
	Personnel costs	totcrewwage
	Repair & maintenance costs	totrepcost
	Subsidies on investments	subinvest
	Total assets	assets
	Value of quota and other fishing rights	totrights
Socio-economic variables	Value of unpaid labour	totunpaidlab
	Unpaid labour	unpaidemp
	Engaged crew	totjob
	FTE national	totnatfte
	Total hours worked per year (engaged crew)	hrworked

The "Other Fishing Region (OFR)" group (supra region column) is selected to exclude European water fisheries from the STECF data. Next, we choose the geographical indicators IWE (International waters), NEU (No European waters), and NGI (no geographical indicator) (geo indicator column). A supplementary geographic filtration to keep only tropical fisheries of the Atlantic and the Indian oceans is not possible (issue 1: geographical aggregation). Furthermore, a filtration by fishing métier to keep only tuna fisheries is not possible (issue 2: specific aggregation). Finally, economic and social variables for particular years and fleets can be declared for the larger segment. This vessel-size aggregation is also present in the corresponding landings (issue 3: sporadic vessel-size aggregation).

To obtain economic and social variables for artisanal and industrial tropical tuna fisheries in the Atlantic and Indian oceans, and for comparable years, we developed three main steps: (1) vessel-size disaggregation of variables for fleets and years concerned (part. 3.2.1.), (2) specific disaggregation of variables to keep only economic and social values relative to tuna fisheries (part. 3.2.2.), and (3) a geographical disaggregation to keep only economic and social values in the tropical Atlantic Ocean and the Indian Ocean (part 3.2.2.).

After these disaggregation processes, a dataset of economic and social variables for tropical tuna fisheries in the Atlantic and Indian oceans is obtained. Using these variables, nine indicators of tropical tuna fisheries' sustainability performances are calculated: two for the ecology dimension (fuel use intensity and carbon footprint), five for the economy dimension (Importance of energy costs, energy efficiency, margin rate, net profit, return on fixed tangible assets (RoFTA)), and three for the social dimension (work productivity, created FTE, average salary). This second dataset of the dashboard is composed of 628 lines and 62 columns, i.e., 10 are fleet characteristics (Table 4), 35 are STECF technic, economic, and socio-economic variables (Table 2.3) corrected after disaggregation processes and four are supplementary economic environment variables (gasoil price, barrel price, SKJ, and YFT price). Details of the calculation method of all indicators with the R code can be found in Supplementary Material 2.2. Raw public data for the dashboard application is available in the file "ICCAT IOTC and STECF raw data" of the repository.

*Tableau 2.4 : Number of fleets (Flag*fishing gear*vessel size) by fleet characteristics, for which economic, social and ecologic indicators can be calculated.*

Fleet characteristics		Atlantic Ocean	Indian Ocean
Fishing gear groups	Purse seine	8	3
	Longline	12	11
	Gillnet	2	1
	Other	30	2
Vessel size segments	> 40m	10	7
	24m - 40m	10	5
	18m - <24m	6	1
	12m - <18m	6	1
	10m – <12m	9	1
	0m - <10m	11	2

With fishing gear groups corresponding to the following fishing gears:
. Purse seine: purse seine;
. Longline: vessels using hooks;
. Gillnet: Drift and/or fixed netters;
. Other: Demersal trawlers and/or demersal seiners, Vessels using pots and/or traps, pelagic trawlers, Vessels using other passive gears, Vessel using active and passive gears, Vessels using polyvalent active gears only.

2.4 Vessel-size disaggregation

For some fleets and years, the value of economic and social variables collected by the STECF and corresponding landings (FAO's raw data) are aggregated in the larger fleet segment for confidentiality issues (i.e., statistical individuals correspond to year*fishing gear*flag instead of year*fishing gear*flag*vessel-size). In our dataset, 56 % of fleets were aggregated (i.e., 48 observations), representing 30.4 % of related reported catches. Only fishing effort and capacity variables remained available at the fleet segment resolution (Table 3). In our dataset, 22%, 57% and 21% of aggregated fleets came from industrial (>24 m), semi-industrial (12-24 m) and artisanal fleets (<12 m), respectively.

We assume a positive relationship between fishing effort and catch to proceed to the disaggregation of economic and social data. Moreover, the exploitation cost and revenues are expected to correlate positively to the fishing effort and catch, respectively.

The objective is to select an effort variable among eight of them (Table 3) that allows disaggregation of economic and social data avoiding distortion of reality as much as possible. Based on non-aggregated fleets with several vessel size segments (44% of the dataset), we simulate an aggregation of economic and social variables, i.e. a sum, then an allocation to each vessel size (Figure 1) using different fishing effort variables. After the disaggregation simulation, we calculate the gap between the original - economic or social - value and the simulated value (equation 1). A Wilcoxon test is performed to test if the gad differs from zero.

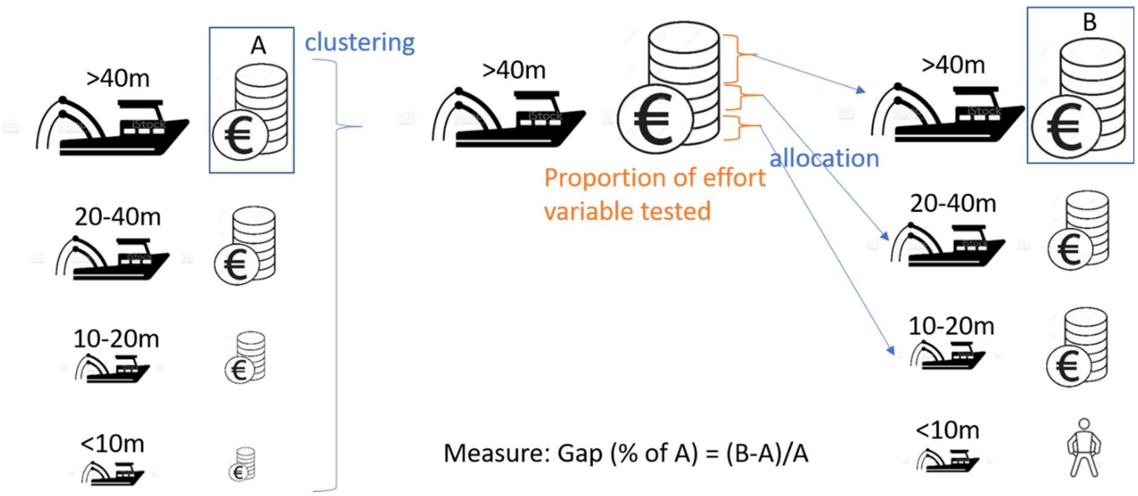

Figure 2.1: Schema of the simulation of economic and socio-economic data disaggregation. The interest measure is an example of gap calculation concerning an economic value in euro (e.g. value at landing, energy costs, etc.) for baitboat fishing fleet belonging to the largest fleet segment (> 40m). Here a positive gap is simulated between A and B with the disaggregated value B larger than the initial value A. The tested method leads to an overestimation of the variable for large vessels (>40m) and an underestimation for smaller vessels (<10m). Only 4 of the 6 size categories (see table 2.4) are shown in this schema.

We found no significant difference between the initial value and the simulated value for the effort variable in total kilowatts (kW) (Table 2.5), whatever the gear and the flag (more information on groups of gears, size segments, and flags with significant differences is available in Sup. Mat. 2.3 Table S2). The total kW by fishing days is chosen for the vessel-size disaggregation procedure.

$$(1) \qquad Gap_{f,y} = \frac{\sum Aggregated\ value_{\ f,y}\ x\ \left(\frac{Fishing\ effort_{f,l,y}}{Fishing\ effort_{f,y}}\right)\ -\ \sum Initial\ value_{f,l,y}}{\sum\ Initial\ value_{f,l,y}}$$

Where f: fleet, y: year and l: length category or size segment. Gap values are estimated for both economic or economic and social indicators.

For aggregated data, economic and social variables are allocated to each fleet segment relative to its fishing effort in total kW by fishing days (equation 2). For example, the Spanish purse seiners larger than 40 m in 2012 represented 98% of the total effort (in total kW by fishing days) of the clustered Spanish purse seine fleet (i.e., all vessel size segments summed).

Therefore, this percentage value was applied to the economic and social value of this cluster of the Spanish fleet in 2012.

*Tableau 2.5 : of Wilcoxon's tests applied to the results of the disaggregation procedure for each effort variable. The bold character indicates the retained effort variable for the disaggregation procedure in our case study. For more details, see the Sup. Mat. 2.3. (no significant: ns, p < 0.05: *, 0.01 < p < 0.05: **, p < 0.01: ***, p << 0.01: ****).*

Fishing effort variables tested		Statistical significance					
		*	**	***	****	ns	Total number of fleet groups tested
kW days at sea	kwseadays	0	0	0	2	2	4
Maximum days at sea	maxseadays	0	1	1	7	5	14
Fishing days	totfishdays	0	1	1	5	7	14
Number of fishing trips	tottrips	2	1	0	3	8	14
GT fishing days	totgtfishdays	0	1	0	6	7	14
GT days at sea	gtseadays	0	0	0	2	2	4
kW fishing days	totkwfishdays	**0**	**0**	**1**	**3**	**10**	**14**
Days at sea	kwseadays	0	0	0	2	2	4

(2) $$Value_{fleet,y} = Value_{cluster,y}\ x\ \frac{Fishing\ effort_{fleet,y}}{Fishing\ effort_{cluster,y}}$$

2.3.4. Filtration of tuna fisheries and allocation to each ocean

The socio-economic variables are gathered for non-European water fisheries, in the global oceans ("Other fishing region" scale) and for all targeted species. The STECF website provides landing data in weight and value by FAO areas, species and fleets ("STECF 20-06 - Landings_all_fao.csv") with a similar fleet resolution of the economic and social dataset (flag*gear*vessel-size*year). FAO areas 51, 57 (Indian Ocean), 34 and 47 (Atlantic Ocean) are selected to keep tropical fisheries' landings. We select only species that are exploited or bycatch by tropical tuna fisheries (Supplementary material 2.4). The no-tropical tuna fisheries, e.g. small pelagic fishery or bluefin tuna fishery, represent 3% and 0.3% of the total catch by weight for all FAO areas of longliner fleets and purse seiners, for example (Table 2.6).

Tableau 2.6: Average percentage of catches from fleets by fishing gears (2009-2019)

Fishing gear code	Percentage of tropical catches
DFN	12.7
HOK	97
PGP	60

PMP	58.6
PS	99.7

DFN: Drift and/or fixed netters; HOK: Vessels using hooks; PGP: Vessels using polyvalent active gears only; PMP: Vessel using active and passive gears; PS: purse seine.

2.4. General patterns

The main objective was to provide a dashboard of sustainability indicators of holistic ecological, technical, economic, and social criteria of fishing fleets applied to tropical tuna fisheries. This dashboard can be reused, replicated, and adapted for different case studies. A monitor of indicators is available[13] using the RStudio Shiny app (Chang et al., 2023) to visualize indicator results by fleets and years. This tool permits an interaction with the open data for a first data exploration. Search and sort are enabled and accessible in any web browser.

A total of 24 ecological, technical, economic, and social indicators for 356 fishing fleets are described in the dashboard (Figure 2.2-a). To clarify the figure, the technical indicator is integrated into the ecological dimension because highly specific to purse seine fisheries. Economic and social indicators are available for recent years and particular fleets only, due to a lack of information on tropical tuna fisheries by RFMOs (Figure 2.2-b). Otherwise, economic, and social indicators can only be monitored for European fleets complying with the European Data Collection Framework (DCF).

Ecological indicators linked to the stock status can be calculated over a long period thanks to fish stock analysis (FSA), which allows for a time series reconstruction of stock biomass. Specific ecological indicators that inform on bycatch (in quantity and quality) and discards, require human observer data or electronic observation on board which are available for less than 10 years (Heidrich et al., 2022). Likewise, catch-size data (used for the calculation of juvenile rate in the weight of catch) needs a sample on board or at the port, available for recent years. Observer and landing data are generally well provided for industrial fleets but still few for artisanal fleets (lack of space on board to accommodate an observer, no landing facilities in place, etc.) (Lewison et al., 2004). Nevertheless, observer data reporting in artisanal fisheries is underway (Bartholomew et al., 2018).

[13] http://halieut.agrocampus-ouest.fr/discardless_app/acv_dashboard/

Generally, artisanal fleets in southern countries remain largely unmonitored in official statistics (e.g., landings in weight and value, variable and no-variable costs of companies such as fuel consumption, etc.). The risks of data-poor case studies are weak coastal state implications in fisheries management while these fleets contribute greatly to the economy and food security of people (Belhabib et al., 2018; Chassot et al., 2019; Kolding et al., 2014). This lack of both economic and social data and monitoring for artisanal fleets contributes to their current differential representation with industrial fleets in decision-making commissions (Sinan et al., 2021). Scientists and managers of coastal and fishing countries must not forget the importance of small-scale fisheries in contributing to the Sustainable Development Goals (Said et al., 2019; Bitoun et al., 2024) and, therefore, consider approaches to assessing their sustainability. Finally, our work highlights the lack of available public data by exploring several public datasets for estimating indicators.

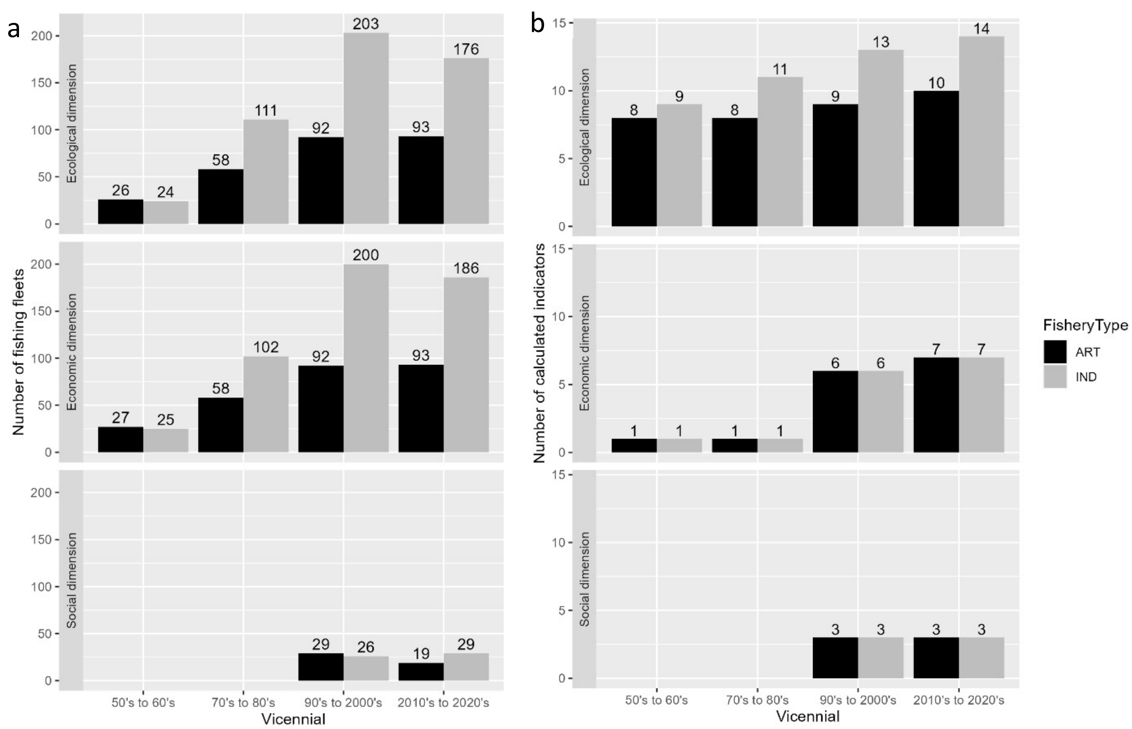

Figure 2.2: a- Number of tropical tuna fishing fleets concerned by the dashboard and b- number of calculated indicators, by decade and dashboard dimensions (ecological, economic and social). The fishery type corresponds to industrial fleets (IND) and artisanal fleets (ART). For ecological indicators, the fishery type corresponds to RFMOs definition of fishing fleets. For economic and social indicators, we assume that industrial fleets correspond to vessel length segments > 24 m to simplify the data presentation in this figure.

2.5. APPLICATION AND FUTURE DIRECTIONS

In the Atlantic and Indian Oceans, different industrial fishing gears are harvesting tropical tuna stocks: purse seiner, longline, gillnet and baitboat (Coulter et al. 2020). Each fishing gear has different technical characteristics (mesh size and net height, hook type and size for the longline, and bait for the baitboat fishing mode (FAD or free swimming school) for the purse seine). Each fishing practice deploys its fishing effort with different direct impacts on exploited stocks (i.e. biomass of mature or no mature tuna catches) and different indirect impacts on the ecosystem (i.e. retained key biomass for the ecosystem because of sensitive species bycatch). The dashboard developed in this study permits the exploration of the various ecological, technical, economic, and social dimensions of the sustainability of these different fishing gears and fishing métier operating by each nationality assessed. This dataset of 24 indicators on 356 tropical tuna fishing fleets (from 1950 to 2019) can be used by fishery scientists but also experts and other stakeholders interested in identifying the strengths and weaknesses of different fleets, fishing gears, metiers and fishing strategies, or even assess effectiveness of fisheries management e.g., yellowfin tuna quota implementation in 2017 in the Indian Ocean (IOTC Resolution 16/01) to provide management advice for the sustainability of fisheries. The fleet level has a higher resolution for data reporting and is compatible with anonymised information for fishing companies. This dataset allows exploring how fishing strategies can be driven by the economic context (i.e. price of tuna, price of fuel, etc.), as done by Floc'h et al., (2008) and Guyader et al., (2013) for French fleets case studies.

In the European scientific community, many scientists and stakeholders remain sceptical about the quality of STECF data collection because the collection protocol seems unclear and still incomplete (i.e., lack of fishing subsidies amount data, even though this variable is included in the DCF). The geographical aggregated information for tropical tuna fisheries makes the scientific community reluctant to use this source of information for tuna fishery research. This disaggregation work is an essential first step, and comparing these dashboard results with specific case studies of socio-economic evaluation or fleet fuel consumption might be a further task to assess the reliability of the European DCF data.

For the other tropical tuna fishing fleets, the RFMOs should collect economic and socio-economic data (resolutions) not currently available in the public domain. Once available, the dashboard approach could be applied to this new data source. Finally, this dashboard has been constructed for an application in the Atlantic and Indian Ocean based on ICCAT and IOTC data availability, but it could be extended to:

- Pacific tropical tuna fleets concerning ecological indicators: the Pacific RFMOs (https://www.iattc.org/, https://www.wcpfc.int/home) are providing public data on tuna fisheries similar to data from the Atlantic and Indian RFMOs (https://www.iccat.int/en/, https://iotc.org/) (i.e. total estimated catch and effort by year, flag, gear, species or set type for purse seiners, stock assessments, bycatch and size data), making this dashboard generalisable to the Pacific fleets *a priori* ;
- European fleets in the Pacific Ocean concerning economic and social indicators: The dashboard dataset provides access to the socio-economic indicators for European fleets in the Pacific Ocean, even though they were not the focus of our study.

2.6. DATA SOURCES

Primary raw data:

- Regional Fisheries Management Organizations Catch data from Task 1 (T1 – Nominal catch only data) and Task 2 (T2 – Georeferenced catch and effort data), were collected from the International Commission for the Conservation of Atlantic Tunas (ICCAT - www.iccat.int) and the Indian Ocean Tuna Commission (IOTC – www.iotc.org);
- Economic and socio-economic data were collected from STECF-EU Fleet Economic Performance (v. STECF 21-06) for the Annual Economic Report (AER) (stecf.jrc.ec.europa.eu/dd/fleet);

Secondary raw data:

- Biomass (B), Fishing mortality (F), Species trophic level (TL), stock parameters, were collected from RFMOs secretariat stock assessment report or bibliography;
- The tuna price: Pacific Islands Forum Fisheries Agency (FFA) (www.ffa.int);
- The oil barrel price: INSEE statistics (www.insee.fr/en/statistiques/serie/010002077).

2.7. REFERENCES DU CHAPITRE 2

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3. QUAND L'ECONOMIE RENCONTRE L'ECOLOGIE, EST-CE VRAIMENT CONFLICTUEL ? UNE APPROCHE TABLEAU DE BORD POUR EVALUER LA PERFORMANCE DE DURABILITE DES THONIERS SENNEURS TROPICAUX EUROPEENS

When economy meets ecology, is it truly conflicted? A dashboard approach to assess the sustainability performance of European tropical tuna purse seine fisheries

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Keywords

Indicators, environment, socio-economic, multi-criteria evaluation, fisheries management, Fish aggregating device (FAD)

Abstract

The development of an ecosystem approach to fisheries management makes the assessment of fisheries' sustainability performance a priority. This study examines European tropical tuna purse seine fleets as a case study, employing a multidisciplinary dashboard approach to evaluate historical and current sustainability performances. The aim is to enhance comprehension of the interconnected dimensions of sustainability and pinpoint management policy priorities.

Using 18 indicators, we assessed the environmental, economic and social sustainability performances of European tropical tuna purse seine fleets, comparing them with other industrial tropical tuna fishing fleets in the Atlantic and Indian Oceans. The analysis also explored the temporal trend of sustainability performance for European tuna purse seiners from 2009 to 2019.

Our results suggest that, compared with gillnetters and longliners, purse seiners and baitboats have greater species-based selectivity, thereby catching fewer endangered, threatened or protected species, but a lower mature tuna catch rate, thus capturing more juveniles. We identify likely gaps in bycatch data reported by fishing on fish aggregating devices (FADs), due to results regarding selectivity and discard rates that appear inconsistent in the light of the scientific literature.

The greater use of FADs, likely caused by the global tuna market, by purse seiner seems to result in decreased ecological performances, as suggested by an increased carbon footprint per tonne landed. At the same time, it implies a better economic performance in the short-term, with higher net profit, energy efficiency (fuel consumed relative to monetary value created) and catch. For our case study, Ecology and Economy might seem to be in conflict from a short-term perspective. However, consideration of the long-term impacts of FAD fishing and market incentives for fishing on free schools should lead purse seiner fleets to reduce drifting FAD fishing and promote more sustainable fishing practices.

3.1. Introduction

Fisheries, including tuna fisheries, are facing a crisis due to the decades-long increase in fishing power, resulting in a substantial increase in fishing effort and excessive fishing pressure worldwide. This increase has been fuelled by human population growth and rising demand for seafood (Roberts, 1997; Pauly and Zeller, 2003; Pauly, 2008; FAO, 2022). As a major source of protein for humans, several tuna stocks are experiencing overfishing in the global ocean (Xie et al., 2020). In 2020, the global catch of the seven main tuna species, namely albacore (Thunnus alalunga), bigeye (Thunnus obesus), bluefin (Thunnus thynnus, Thunnus maccoyii and Thunnus orientalis), skipjack (Katsuwonus pelamis) and yellowfin (Thunnus albacares), was 4,8 million tons, representing 6 % of global marine catches (FAO 2022). A holistic sustainability assessment of these key fisheries for the global seafood market is needed to understand how the biological and ecological status of both resources and ecosystems have changed with the fishery economies and what lessons need to be learned to ensure food supply security.

Tuna fisheries resources are managed by regional fisheries management organisations (RFMOs), which are mandated by members represented by both fishing and coastal countries to assess pelagic resources, especially tunas, tuna-like species (Scombridae, Istiophoridae and Xiphiidae) and pelagic sharks. Within this framework, the management target agreed upon by member states according to international commitments is the maximum sustainable yield (MSY), defined as the largest amount of biomass that can be extracted over the long term from a fish stock under existing environmental conditions without affecting its renewal process (Schaefer, 1954). The MSY is stock-specific and does not consider ecosystem interactions, although these warrant consideration when assessing the environmental impacts of fisheries. Because tunas are top predators, they are considered keystone species in marine pelagic ecosystems. As such, they play a significant role in open ocean ecosystems due to their influence on marine food web structure and dynamics (Estes et al., 2016; van Denderen et al., 2018). Consequently, their decline can initiate trophic cascades (Heithaus et al., 2008) and jeopardise the resilience and stability of marine resources (Kerr et al., 2017; Artetxe-Arrate et al., 2021). Other important interactions result from the bycatch of non-target species that gets discarded. Such discarding can be done for legal reasons in the case of protected species (sea turtles, marine mammals, some sharks, and rays) or commercial ones in the case of low-value species, which is considered wasteful of marine biomass. To respond to these issues, tuna RFMOs (tRFMOs) are conducting more studies on these interactions and monitoring impacts on non-target species (Juan-Jordá et al., 2018). Technical measures to reduce bycatch should contribute to developing an ecosystem approach. However, as management objectives and the definition of fishing limits or quotas are still based mainly on MSY, scientists warn of the need for a more precautionary approach (Karim et al., 2020; Hornborg et al. 2019).

The purse seine is the most productive tropical tuna fishing gear. In the Atlantic and Indian Oceans, the main industrial tropical tuna purse seine fleet flags are France and Spain, targeting skipjack (Katsuwonus pelamis, SKJ) and yellowfin (Thunnus albacares, YFT) tuna, with the bigeye (Thunnus obesus, BET) as a valuable bycatch specie. The tropical tuna purse seine fishery develops two fishing mode: fishing on free school (FSC) and fishing on drifting fish aggregating devices (FAD). In both these oceans, other industrial tuna fishing gears are also deployed to exploit tropical tuna stocks, including longline, gillnet, and pole and line (Coulter et al., 2020). Each fishing gear has different technical characteristics (mesh size and height of nets, hook type and size for the longline, type of bait for pole and line, time of a fishing operation and whether the technique is active or passive), which lead to different fishing efforts, different direct impacts on exploited stocks and different indirect impacts on the ecosystem.

The goal of the present study is to demonstrate how a dashboard approach can be applied to the various sustainability dimensions in fisheries. Taking the activities of European Union tropical tuna fishing fleets as a case study, we aimed to identify the strengths and weaknesses of different fleets, fishing gears, metiers and fishing strategies. The fleet scale is the highest resolution for data reporting due to the anonymisation rules of fishing companies. To improve our understanding of how sustainability dimensions interact, it is necessary to monitor fleet performances over time. This can reveal the strengths and weaknesses of different fishing activities and then allow adapted management strategies to be proposed for those fleets (Capello et al., 2023).

Under the constraint of the data available, the initial step involved constructing a dashboard to allow the comparison of fishing strategies and performance monitoring over time. We then investigated potential factors influencing changes in fishing strategies and their consequences for various sustainability dimensions.

In fisheries management, sustainability has usually been defined with reference to the catch level that can be maintained over time (e.g. maximum sustainable yield assessment) and to ecological impacts of fishing (e.g. on bycatch species or seafloor integrity), without considering economic, human, or social goals. Based on the conservation paradigm of protecting the ecological system, numerous scientific studies have used a multidimensional approach (ecological, economic, social, governance, etc.) to assess the sustainability of fisheries using dedicated scoring (e.g. the FPI method, Anderson et al., 2015; the RAPFISH technique, Pitcher and Preikshot, 2001; the VALDUVIS tool, Kinds et al., 2016). Seafood labelling also uses a multi-criteria approach with a rating based on selected criteria to indicate the degree of sustainability of a fishery (e.g. Marine Stewardship Council, Friend of the Sea or the French Pêche durable labels). Not many labelling approaches yet include socio-economic impacts, except Friend of the Sea (FOS) labelling (Lecomte et al., 2017). A few studies have worked on a broad multidimensional dashboard of theoretical sustainability indicators applied to the fishing industry, but none has yet been based on a case study (Danto et al., 2021; Dewals and Gascuel, 2020).

The objective of multi-criteria evaluation methods is to identify, according to selected evaluation criteria, practices of a given fishery that need to be improved, those that need to be promoted, and existing spaces and levers for improvement. They do not tell us whether fleets can perform well in all dimensions simultaneously. In a multidimensional and intertemporal sustainability assessment study based on the RAPFISH methodology, Murillas et al. (2008) warned of the potential negative consequences of seeking better fishing capacity (e.g. by increasing the number of vessels) on the ecological dimension (e.g. an increase in discards), but could not explain causal relations among different variables.

The challenge is to find how a dashboard approach can highlight multidimensional fleet sustainability performance and how inter-dimensional interactions can be identified for more efficient policy recommendations and fishery management options.

The aim of our study is to respond to this challenge by constructing a relevant and operational dashboard for the sustainability assessment of tropical tuna fisheries that will reveal differences among pelagic fleets, gears and strategies (in the case of purse seiners) exploiting the same resource and help to understand how indicators from ecological, economic and social dimensions interact. In this way, we can examine whether a fishing fleet must necessarily have an ecological impact in order to be economically and socially sustainable and whether we can find paths for improvement.

In this context, our study (i) compares recent sustainability performances (2015–2019) among different European tropical tuna purse seiner fleets and (ii) among different tropical tuna pelagic fishing fleets (baitboat, gillnet, longline) and (iii) analyses the co-evolution of sustainability indicators for European tropical tuna purse seiner fleets over a longer period (2009–2019).

3.2. Materials and methods

3.2.1. Dashboard construction: selection of sustainability assessment indicators

The sustainability of fisheries can be addressed from different angles or dimensions, such as the related biological, ecological, economic, socio-economic, market and finance or socio-cultural systems. In a dashboard approach, the sustainability criteria associated with each dimension are defined as sustainability targets or objectives. For example, in the biological and ecological dimensions, fisheries minimise their impact on stocks, the seafloor, sensitive species, etc. Indicators are mathematical formulations for given criteria and are notably used to determine whether a management objective has been reached. Different indicators can assess the same criterion e.g. the status of the stock targeted by fisheries (in other words, does the fishery base its activity on stocks that are in good condition?) can be assessed using an indicator of overfishing stocks (related to the Fmsy target: the fishing pressure able to deliver, on average, the maximum sustainable yield) and an indicator of overfished stock biomass (related to the Bmsy target).

Dimensions, criteria and indicators were selected from the peer-reviewed literature on theoretical multi-dimensional dashboards, and ecological indicators for tuna fisheries identified in literature, technical reports, and fishery statistics (Sup. Mat. 2.1). From this review, we selected indicators based on criteria ranked as according to: (i) the suitability of the scale of the indicator information to assess the sustainability at the fleet level, (ii) whether public data were available or easy on an annual basis, (iii) whether the scale of public data provided a fleet-level resolution or could be adapted to one (Sup. Mat. 2.1). Specific ecological indicators for tuna fisheries were related to the main characteristics and challenges for tropical tuna fisheries in both the Atlantic and Indian Oceans and added to the analysis (Sup. Mat. 2.2).

We compiled an initial list of 24 indicators distributed among the ecological (13 indicators), technical (1 indicator), economic (7 indicators) and socio-economic (3 indicators) dimensions of sustainability for tropical tuna fisheries (Table 3.1). The dashboard encompasses the following criteria: the status of targeted stocks, the ecological footprint of fleets on targeted stocks and the marine ecosystem, the temporal trend of tuna catches, economic health, and ecologic efficiency of energy (i.e. economic productivity, fuel use intensity), employment stability and wage levels. The procedure of data collection and calculation of indicators are detailed in Sup. Mat. 2.3. The dataset used for analysis corresponds to indicator results from Table 3.1 calculated annually for 59 and 43 fishing fleets (flag x fishing gear combinations) in the Atlantic and Indian Oceans, respectively. Ecological indicator results were available for all fleets for the 1950 to 2019 period (except for carbon footprint and FUI indicators) for all fleets. The other indicators (economic, socio-economic and those related to carbon impact) were available for 2008–2019 for the European tuna purse seine fleets (French and Spanish purse seiners in Atlantic and Indian Oceans).

Different indicators can provide redundant information for the same criteria of sustainability. To avoid redundancy in the analysis and keep only uniquely informative indicators, we conducted a pairwise Pearson correlation test between all indicators, using R and RStudio software (R Core Team, 2023; RStudio Team, 2023) (linear correlation matrix available in Sup.

Mat. 2.4). Based on this matrix, we identified collinearity between indicators related to stock biomass (B/Bmsy, B/B0, SSB/SSB0, SSB/SSBmsy) and indicators related to the impact on climate change (carbon footprint and fuel use intensity). We kept the spawning biomass stock indicator (SSB/SSBmsy) to express the current stock status relative to the SSBmsy target, while avoiding short-term variability due to recruitment changes. We retained the fuel use intensity (FUI) indicator is the most commonly used indicator to indirectly express the impact on climate change (Basurko et al., 2022; Bianchi et al., 2022; Parker and Tyedmers, 2015). Finally, the dataset analysed consisted of nine ecological indicators, six economic indicators and three socio-economic indicators for 59 and 43 fishing fleets in the Atlantic and Indian Oceans, respectively.

3.2.2. Statistical analysis

We present the current performance of the four European tuna purse seine fleets based on average figures for the 2015–2019 period using radar diagrams. Radar diagrams provide an overview of the dashboard results. For each indicator, 0 was assigned to the least sustainable value obtained among the four fleets, and 1 to the most sustainable value based on interpretation of the indicator results in Table 3.1.

We also used principal component analysis (PCA) for two purposes: (1) characterising individuals (e.g. fishing fleets) based on variables (e.g. indicators of sustainability performance), and (2) identifying correlation links between these variables.

To conduct a PCA, the dataset must have no missing values. In the dashboard dataset, indicator values could be unavailable for certain years and fleets due to gaps in reported data. For all tuna fleets, 35% of the ecological indicator values and 7% of the economic and socio-economic indicator values were unavailable. The “missMDA” R package (Josse and Husson, 2016) was used to replace missing data with plausible and neutral values derived from a model that considered the similarities between individuals and variables.

A first PCA on ecological indicators was conducted to examine the contrast of ecological sustainability performances among tropical tuna fishing fleets (94 individuals). This analysis was based on the mean values of indicators over the last few years (2015–2019). Since specific ecological indicators, such as discard data, free school catch rate, and fuel use intensity are exclusive to particular fleets, these three indicators were categorised as supplementary variables to mitigate potential biases in fleet typology derived from ecological indicators.

A second PCA was run for the full dataset, considering all indicators for the European purse seiner fleets. We used an economic themascope PCA (Lebart, 1989), in which economic and socio-economic indicators were active variables while ecological indicators were supplementary variables. With the resulting typology of fleet fishing strategies, we aimed to highlight interactions between economic and socio-economic indicators and their potential links with ecological indicators. We considered additional descriptors of the economic environment as supplementary variables in the themascope PCA to examine how economic performances of the fishing fleets were linked to their environment. The variables of the economic environment were: the global average annual price of fuel (INSEE, 2022), skipjack and yellowfin prices (Campling et al.,, 2022), and the annual total catch by fleet. Economic and socio-economic data were available from 2008 to 2019. This PCA had 40 statistic individuals (four European tropical tuna fleets over 10 years).

Tableau 3.1: Synthetic table of indicators calculated, analysed and how they should be interpreted

Dimension	Indicator name	Criteria	Interpretation aid	Analysed Indicators
Biological & Ecological system	Stock assessment reliability	The fleet exploits fishing stocks based on reliable stock assessment	The higher the score, the more the fleet is exploiting a stock whose stock assessment quality is good (Low uncertainty score)	X
	Overfishing stocks	The fleet exploits fishing stocks which are not subject to overfishing	The higher the score, the more the tuna stocks, targeted by the fleet, in proportion of catch, are overexploiting.	X
	Stock biomass (relative to Bmsy)	Tuna stock biomass is not overfished relative to MSY	The higher the score, the more the tuna stocks, targeted by the fleet, have large biomass relative to Bmsy	collinear
	Spawning stock biomass (relative to SSBmsy)	Tuna stock spawning biomass is not overfished relative to MSY	The higher the score, the more the tuna stocks, targeted by the fleet, have large spawning biomass relative to SSBmsy	X
	Stock biomass (relative to B0)	Participation capacity of biomass of exploited stocks in the ecosystem in a pristine state (without fishing)	The higher the score, the more the fleet is exploiting stocks whose biomass is close to the virgin state and thus available for the functioning of the ecosystem	collinear
	Spawning stock biomass (relative to SSB0)	Participation capacity of spawning biomass of exploited stocks in the ecosystem in a pristine state (without fishing) - Protection of juveniles	The higher the score, the more the fleet is exploiting stocks whose spawning biomass are close to the virgin state and thus available for the functioning of the ecosystem	collinear
	Mature catch rate	Exploitation diagram is consistent with protection of juveniles	The higher the score, the more the fleet is exploiting mature fish, thus limiting its impact on stocks (Tuna length L > L with 50% of maturity)	X
	Species-based selectivity	The fishery is selective and impacts only the target species	The higher the score, the more the fleet is selective and fewer non-targeted species are impacted	X
	Discard rate	The fishery does not waste biomass	The higher the score, the more the fleet discards biomass and the higher the ecosystem impact	X
	Sensitive species catch rate	Minimum impact on the least productive biomass (sensitive species)	The higher the score, the greater the fleet's catch of conservation-status species (sharks, turtles) and the higher the ecosystem impact	X
	Bycatch TL mean	Bycatch and discards concern species of low trophic level	The higher the score, the less the fleet has an impact on high trophic levels in the ecosystem	X
	Fuel use intensity	The fuel use intensity is less by landings in weight	The higher the score, the more the fleet consumes fuel by kilo caught and thus has a potential impact on climate change	X
	Carbon footprint	The carbon footprint is less by landings in weight	The higher the score, the less the fleet emits the most CO2 by kilo caught, and thus has a potential impact on climate change	collinear
Technical system	Effort on Free School	Effort rate on FSC is sufficiently important not to	The higher the score, the less the fleet has a potential impact on	X

		impact the resource or ecosystems	stocks and on bycatch and sensitive species, and thus on the ecosystem	
Economic & Finance system	Variability in catch	Tuna catch is stable: inter-annual variability of tuna catch is low	The higher the score, the more the significant tuna catch changes from one year to another	X
	Importance of energy costs	The energetic dependence is low	The higher the score, the lower the energetic dependence of the fleet (Lowest energy costs relative to the turnover)	X
	Energy efficiency	The economic productivity of energy is good	The higher the score, the higher the economic productivity of energy of the fleet (Greatest gross added value relative to the fuel consummation)	X
	Margin rate	The economic profitability is good	The higher the score, the higher the economic productivity of the fleet (Highest gross operating profit relative to the gross added value)	X
	Net profit	The economic profitability is good	The higher the score, the higher the economic productivity of the fleet (Highest landings incomes with lowest total costs)	X
	RoFTA	The capital productivity is good	The higher the score, the higher the return of tangible assets (RoFTA) of the fleet (Highest gross operating profits relative to physical capital values)	X
	Variability in YFT's prices	Tuna price is stable: inter-annual variability of tuna price is low	The higher the score, the more the significant yellowfin tuna price changes from one year to another	X
Socio-economic system	Work productivity	The work productivity is good	The higher the score, the higher the work productivity of the fleet (Highest gross added value relative to the number of full-time equivalents)	X
	Created FTE	Employment is stable across successive year	The higher the score, the greater the number of jobs created (in full time equivalent – FTE) from one year to another. It is not the absolute number of FTE.	X
	Average salary	Salary levels are good	The higher the score, the higher the average salary (Greatest salary costs with regard to the number of full-time equivalents)	X

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3.3. Results

3.3.1. Recent average performances of European purse seiners (2015–2019)

Figure 3.1 displays the comparative dashboard indicators values of the European purse seiners. The French and Spanish fleets in the Atlantic Ocean show similarly higher performances regarding indicators of spawning stock biomass and ecosystem impact (bycatch TL mean, sensitive species catch rate, species-based selectivity, mature catch rate), while exhibiting rather large ratio of fishing on free swimming school (FSC) (Fig. 3.1a). The situation is the opposite in the Indian Ocean, where a common pattern between French and Spanish fleets is only found for the indicators of overfishing stocks and stock assessment reliability.

In the Atlantic Ocean, the French fleet has higher results than the Spanish one for the spawning stock biomass (37%), fuel use intensity (0.48 L fuel.kg-1 of tuna landed), FSC catch rate (45%), bycatch TL mean (4.4) and sensitive species catch rate (conservation status species) (0%), while the Spanish fleet has the highest results on the mature catch rate (50%) and species-based selectivity (99.9%); it matches the French fleet for sensitive species catch rate (0%) and bycatch TL mean (4.4). The Spanish fleet in the Atlantic Ocean has the lowest performance on the indicators referring to stocks and fuel use intensity (0.57 L fuel.kg-1 landed, Fig. 3.1a). Average fuel use intensity (FUI) was 19% higher in the Spanish fleet than in the French fleet in both oceans for the 2015-2019 period.

With regards to economic indicators, Spanish fleets commonly have higher results than the French ones for the margin rate (54%), economic productivity of energy (1.2 €.L-1 fuel) and the importance of energy costs (13.6%) (Fig. 3.1b). The variability in catch and number of full-time equivalents (FTEs) created are higher for the Indian Ocean fleets, particularly for the Spanish Indian Ocean fleets (6% and 278 FTE created, respectively). The Spanish fleets have lower average fisher salary costs and work productivity compared with the French fleets (work productivity of 97 and 116 103 €.FTE-1 and average fisher salary costs of 41.8 and 115.8 103 €.FTE-1). The Spanish fleets have higher net profit than the French fleets (57.4 106 € and 5.6 106 € respectively).

Figure 3.1 displays the absolute dashboard results of the European purse seiners. The French and Spanish fleets in the Atlantic Ocean showed similar good performances regarding indicators of impact on the ecosystem and the spawning tuna biomass (bycatch TL mean, sensitive species catch rate, species-based selectivity, mature catch rate, free school concentration (FSC) catch rate, spawning stock biomass) (Figure 3.1-a). The situation is the opposite in the Indian Ocean, where a common pattern is present only for the indicators of the overfishing stocks, mature catch rate and the indicator of stock assessment reliability. In the Atlantic Ocean, the French fleet has highest results on the spawning stock biomass (37%), fuel use intensity (0.48 L fuel.kg^{-1} of tuna landed), free school catch rate (FSC rate) (45%), bycatch TL mean (4.4) and sensitive species catch rate (conservation status species) (0%). In the Atlantic Ocean, the Spanish fleet has the highest results on the mature catch rate (50%) and species-based selectivity (99.9%) and matched the French fleet for sensitive species catch rate (0%) and bycatch TL mean (4.4). The Spanish fleet in the Atlantic Ocean has the least performance on the indicators referring to stocks and fuel use intensity (0.57 L $fuel.kg^{-1}$ landed). The Spanish fleet's fuel use intensity (FUI) was 19% higher than French fleet's in both oceans in average (2015-2019). With regards to economic indicators, Spanish fleets commonly have higher results than the French ones for the margin rate (54%), economic productivity of energy (1.2 $€.L^{-1}$ fuel) and the importance of energy costs (13.6%) (Figure 3.1-b). The variability in catch and number of full-time employment (FTE) created are higher for the Indian Ocean fleets, particularly for the Spanish Indian Ocean fleets (respectively 6% and 278 FTE created). The Spanish fleets have the lowest results for average salary and work productivity compared to French fleets (respective work productivity of 97 10^3 $€.FTE^{-1}$ and 116 10^3 $€.FTE^{-1}$ and average salary of 41.8 and 115.8 $€.FTE^{-1}$). The Spanish fleets have higher net profit compared to French fleets (57.4 10^6 € and 5.6 10^3 € respectively).

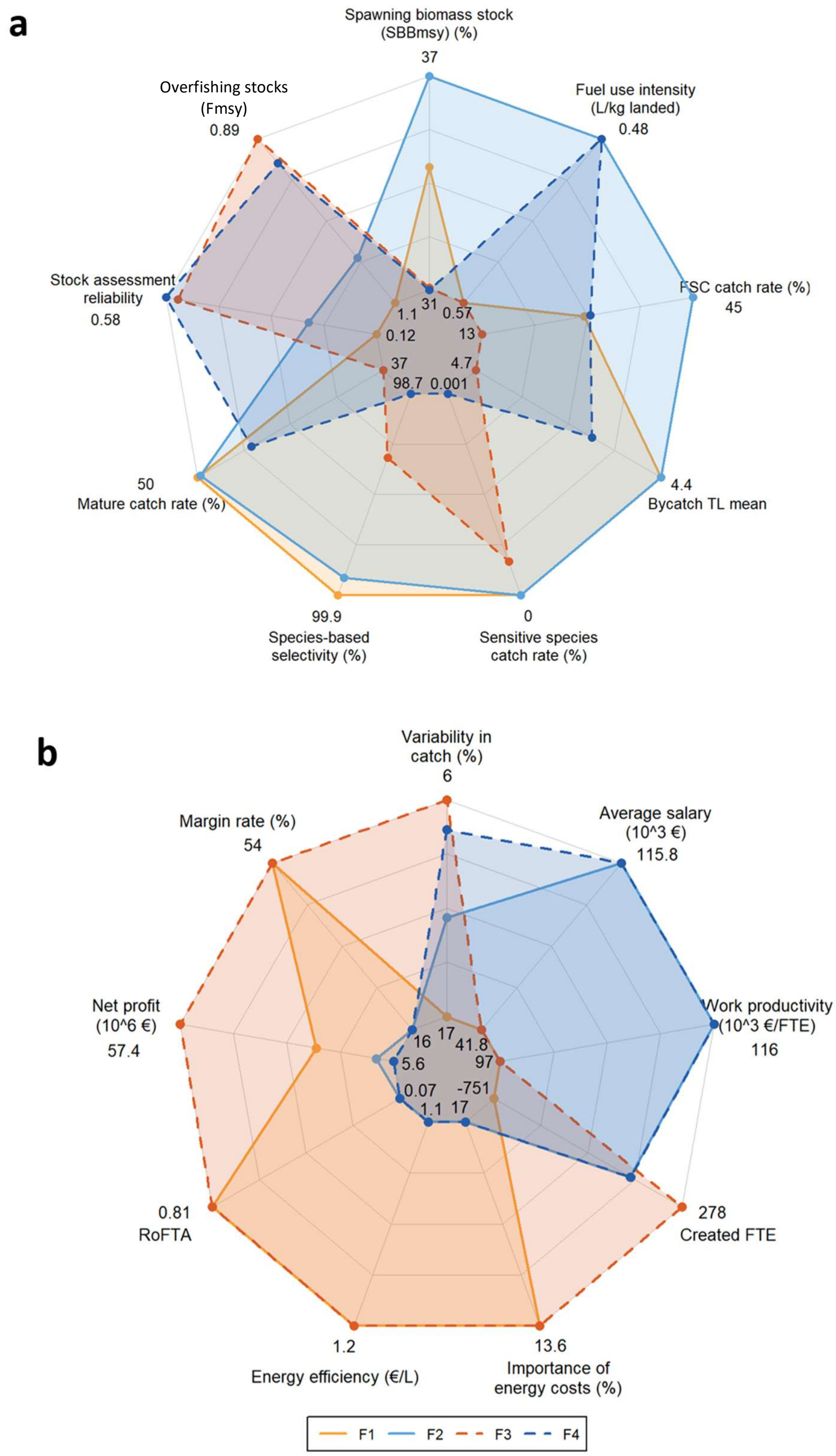

Figure 3.1 : *Current average (2015–2019) of (a) ecological, (b) economic and socio-economic relative performances of European tropical tuna purse seiners (orange colors for Spanish fleets (F1,F3), blue colors for French fleets (F2,F4)) in Atlantic (full lines; F1,F2) and Indian (dashed lines; F3,F4) Oceans. Numbers represent the absolute indicator results. Results shown outside the plot indicate the best performances observed in the population. (which can be under the most desirable situation).*

3.3.2. Comparison of ecological performances of the various fleets and gears in the different oceans

Axis 1 of the ecological PCA is explained positively by several ecosystem impact indicators: the overfishing stocks, mature catch rate, bycatch TL mean, and sensitive species catch rate (Fig. 3.2). This axis is explained negatively by the spawning stock biomass (based on SSB/SSBmsy ratio) (Fig. 3.2a). The fuel use intensity describes axis 1. Fishing gears are displayed along axis 1, the longline fleets having positive coordinates on this axis (Fig. 3.2b). Longliners are characterised by large ecosystem impacts with greater sensitive species catches and a higher mean bycatch TL than other fishing gears, although they caught more mature tuna individuals. This fleet displays the higher dispersion along the axis 1 relative to other fishing gears in both oceans. In contrast, purse seiners and baitboats (i.e. fishing vessels of the pole-and-line fishery) fleets appear characterised by lower ecosystem impacts than other fishing gears, but a greater catch of juvenile tuna catch. Gillnet fleets had intermediate ecosystem impacts. Axis 2 of the ecological PCA is explained positively by the species-based selectivity indicator and partially explained negatively by the overfishing stocks catch rate indicator.

Axis 2 opposes the Atlantic Ocean fleets and Indian Ocean fleets (Fig. 3.2c). The overfishing stocks catch rate indicator is negatively correlated with indicators of good stocks status, i.e. it is linked to B/B0, B/Bmsy and SSB/SSB0 (§3.2.1.). Tuna fleets in the Atlantic Ocean are characterised by more catch from overexploited (B/Bmsy) and overfishing (F/Fmsy) stocks and a better species-based selectivity than fleets in the Indian Ocean. The French and the Spanish fleets differ regardless of ocean considered. In the Indian Ocean, the difference between fleets is related to Axis 1; in the Atlantic Ocean it is related to Axis 2. In the Indian Ocean, the French purse seine fleet catches more mature fish and shows a higher bycatch TL mean and a higher FUI than the Spanish purse seine fleet. In the Atlantic Ocean, the French purse seine fleet has a higher species-based selectivity with more catches on stocks that have a better status and are less intensively fished.

It should be underlined that the free swimming school (FSC) fishing ratio is not represented on the axe1/axe2 PCA plan, while, due to data limitations, results regarding purse seiner are established on average not considering the fishing practice (fishing on FAD vs FSC). Therefore, positive ecological performances of that fleet compared to longliners may mask within-group or between fishing practices variability and should be considered with cautious.

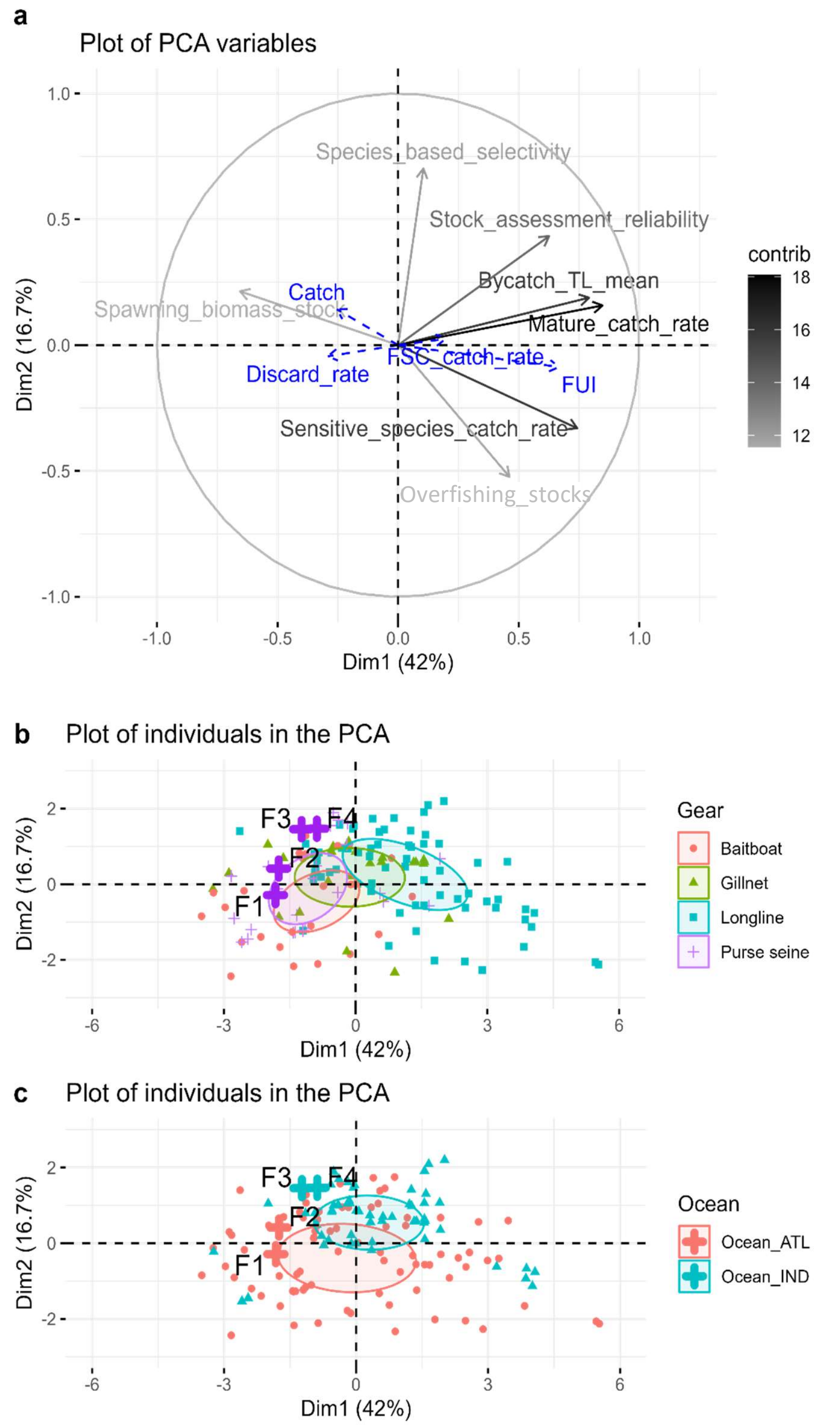

Figure 3.2 : Principal component analysis of mean ecological indicator results for the 2015–2019 period for all tuna fishing fleets in Atlantic and Indian Oceans (Spanish fleets: F1 & F3; French fleets: F2 & F4). (a) Plot of variables. Blue dotted arrows show supplementary variables and black arrows show active variables. The degree of red shading expresses the percentage contribution of the variable to the total inertia of the design. (b) & (c) Plots of individuals colour-coded by ocean (b) and fishing gear (c).

3.3.3. Dynamics of economic and social performances of European purse seiners

Axis 1 of the economic PCA is linked to the economic performance of the fleets (Fig. 3.3a). High values are related to a high capital productivity (return on fixed tangible assets: RoFTA), high economic productivity of energy, high net profit and, to a lesser degree, high margin rate and low share of energy costs in the total costs. The net profit and RoFTA are correlated with high catch, high YFT price and less fishing effort on free swimming schools (FSC rate). Axis 2 (dimension 2) of the economic PCA characterises the two European fleets (Fig. 3.3b). This dimension is explained by a high fuel use intensity (i.e. higher fuel consumption per ton of tuna), more FTEs created, lower average fisher salary costs and, to a lesser degree, by work productivity. Indicators related to species-based selectivity, mature catch rate, variability in catch and variability in YFT prices do not contribute significantly to the Axis 1-2 factorial plane.

The French fleets had higher average fisher salary costs and a more stable number of jobs (in full time equivalents: FTEs) than the Spanish fleets. In 2009, the French fleets were characterised by lower economic performances (smaller RoFTA and a higher share of energy costs) than in the other years (Figs. 3.3b & 3.4a). In contrast, in 2012, the Spanish fleets were characterised by more FTEs created (i.e. instable number of FTEs), a smaller average fisher salary costs and a higher fuel use intensity. There is no difference between oceans for economic or socio-economic performances. Differences only appeared according to the fleet flag (Fig. 3.3b, fig. 3.4a & b).

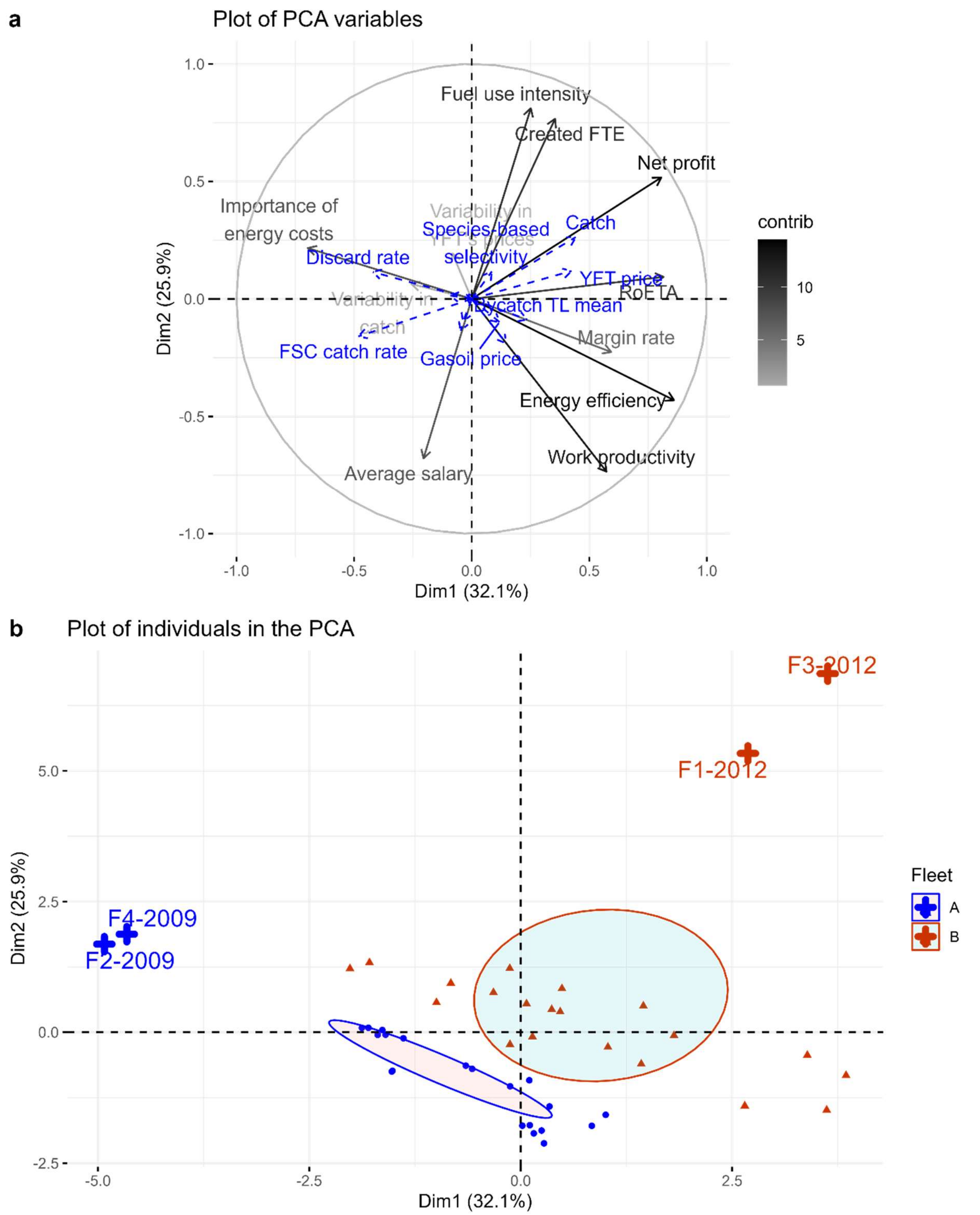

Figure 3.3 : Plots of (a) variables and (b) individuals from PCA of economic and socio-economic indicators (table 1) for European tropical tuna purse seiners over 10 years (2009–2019) in Atlantic (F1, F2) and Indian (F3, F4) Oceans. Variables shown with blue dotted arrows are supplementary variables and black arrows are active variables. The ecological indicators are supplementary variables. The plot of individuals is colour-coded by national fleet (A-French, B-Spanish). On the variable plot (a), the degree of red shading expresses the percentage contribution of the variable to the total inertia of the design.

3.3.4. Monitoring the sustainability performances of European purse seiner fishing fleets

The economic performances over time (i.e. the fleets' positions on axis 1 of Fig. 3.3) show similar dynamics for the French and Spanish purse seine fleets, with higher performances in 2013 and 2017 and lower performances in 2009 and 2015 (Fig. 3.4a). In 2012, a significant difference between fleets can be noted, with a lower performance for Spanish fleets. Regarding carbon and social aspects, negative coordinates on PCA axis 2 suggest a lower carbon impact, higher average fisher salary costs and less FTEs created by the French fleet (Figs. 3.3a, fig. 3.4b). For this fleet, the carbon and social strategy (i.e. fleets' positions on axis 2 of Fig.3.3) trend decreased until 2018 and then started to increase. For the Spanish fleet, the trend was stable over time, except in 2012 when a sharp increase occurs for both FTEs created, and carbon impact (Fig. 3.4b). In both Atlantic and Indian Oceans, and over the whole studied period, the Spanish fleet fishes more on fish aggregating devices (FADs) than the French fleet (Fig. 3.4c). A general increase in the fishing rate on FADs is observed over the studied period. Depending on the fleet, it increases from 45-60% in the early 1990s to 55-90% at the close of the 2000s. This increase is particularly strong for the Spanish fleets in the Atlantic Ocean (from 50 to 70%) and even more in the Indian Ocean (from 55 to 90%). For the French fleets, the increase would be only around 10%, with reported FAD fishing rates at the end of the period around 55 and 70% in the Atlantic and Indian Oceans respectively. These trends result in a growing contrast between flags, with the French and Spanish fleets displaying close fishing rates on FADs at the start of the period but much higher for the Spanish fleets in recent years.

According to available data, the species-based selectivity would be up to 99.5% until 2016–2017, except for the French fleet in the Indian Ocean. This latter fleet exhibited a low selectivity of 98.8% in 2012, a year that is also characterised by a low selectivity for the other fleets. The selectivity remained stable in both oceans. In the Atlantic Ocean, the indicator related to stock overfishing (F/Fmsy) increased from the 1950s until the 1990s for the YFT stock and until the 2000s for the BET stock, reaching 1.6 and 1.3, respectively (Figs. 3.4e & f). Both stocks were suffered from overfishing (F> Fmsy) from the 1990s. After 2005, the ratio value stabilised at around 1.3 for the BET and 0.9 for YFT. In the Atlantic Ocean, the SKJ (eastern stock) shows a stable F/Fmsy of 0.6 (Fig. 3.4e). In the Indian Ocean, the fishing pressure F/Fmsy on the YFT, BET and SKJ stocks increased from the 1980s up to the 2000s, reaching 1.25, 1.1 and 0.65, respectively. The F/Fmsy of the YFT stock was still on an increasing trend. Overfishing of YFT and BET stocks (F> Fmsy) started recently, with the first situation of overfishing of the YFT stock occurring in 2006 (Fig. 3.4f).

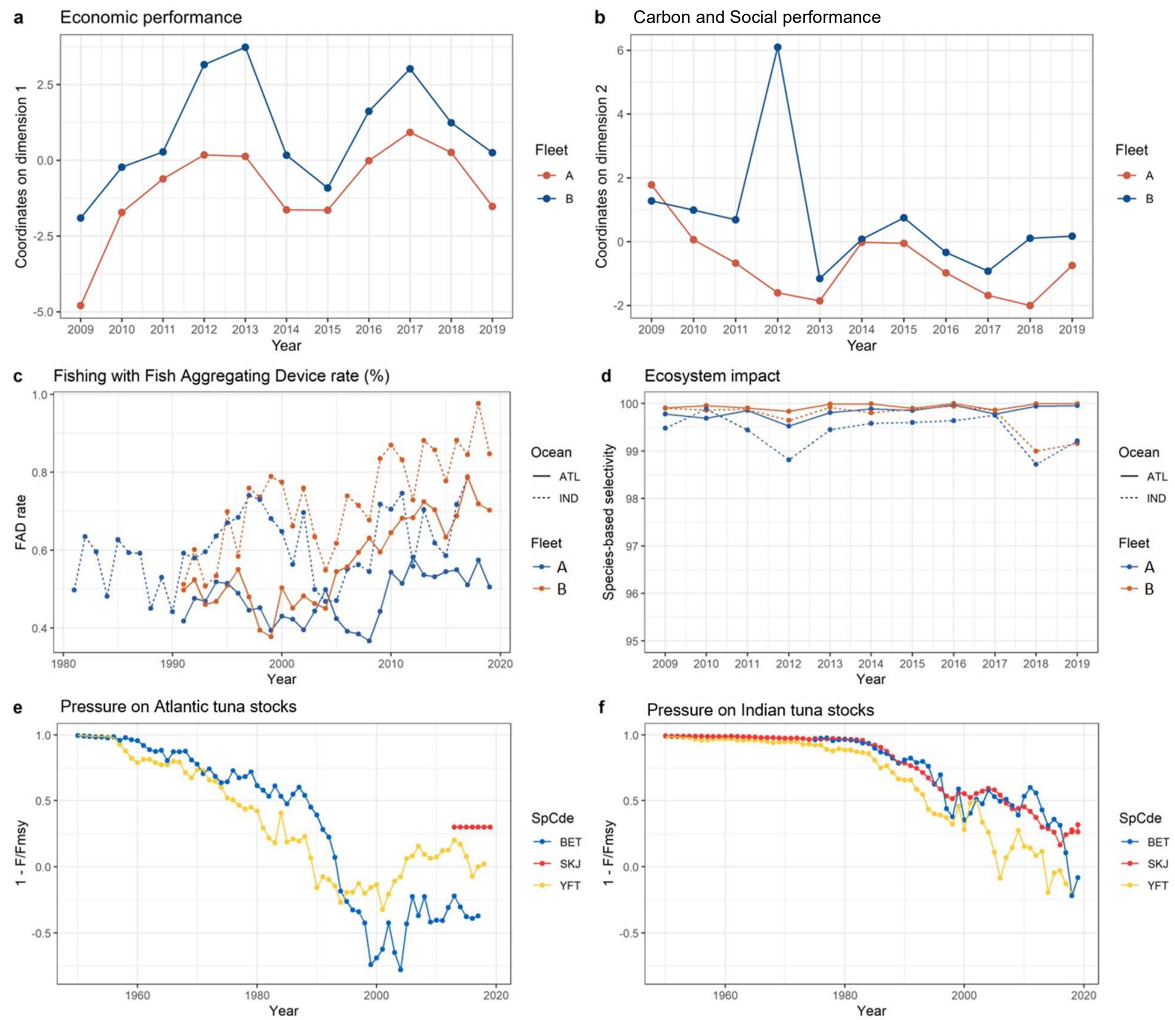

Figure 3.4 : *Plots of purse seine tropical tuna fishing fleets over time. The coordinates on axes 1 and 2 of the economic PCA (Fig. 4) are expressed over time for each national fleet (a & b) (A-French fleet, B-Spanish fleet). The two indicators, rate of fishing with FADs and species-based selectivity, are expressed over time by country and ocean (c & d). The state of the major tropical tuna stocks (1-F/Fmsy) is expressed over time in both Atlantic (e) and Indian Oceans (f) for each species (BET-Bigeye tuna, SKJ-Skipjack tuna, YFT-Yellowfin tuna)*

3.4. Discussion

This study analyses the sustainability of European tropical tuna purse seiners (EU-PS) in the Atlantic and Indian Oceans using a dashboard approach. This technique allows the study of the sustainability of fisheries in a multi-dimensional and multi-temporal framework providing relevant and useful information for policy makers. The analysis was conducted for three sustainability dimensions – ecological, economic and social – for the period from 2009 to 2019. We compared the ecological sustainability of the EU-PS with other fisheries using different fishing gears (longline, gillnet, pole and line) and analysed interactions between indicators of sustainability.

3.4.1. Sustainability of tropical tuna fisheries about tuna stocks and the ecosystem

Concerning the ecological dimension, the dashboard highlights differences in stock-related and ecosystem sustainability performances among the fishing fleets. The ecological sustainability of fisheries depends on the ocean fished and the fishing gear in use. Fleets exhibit a lower species-based selectivity (more bycatch) in the Atlantic Ocean than in the Indian Ocean, independently of fishing gears. This result may be linked to the existence of the "faux-poisson" market in Abidjan, which allows bycatch valorisation (sale on the local market of minor tuna species caught by the tropical tuna fishery but unwanted by tuna canneries) (Amandè et al., 2012). For Romagny et al. (2000), the development of purse seine fisheries on FAD allows for important supply of "faux-poisson", which meets a significant demand for fish from the local populations, resulting in an important local market. A similar market exists in the Indian Ocean due to purse seiners, but is less known. (Quaas et al., 2016) underlined the strong seafood protein dependence of the west Africa region, what could justify a market based on tuna fisheries bycatches. However, we can question this reasoning from an ethical point of view. Thus, the impact of fishing activities on local development, through the catch of marine resources and the indirect effects in structuring the fish market on land, should be explored.

For the time period considered in this study, the Atlantic Ocean fleets differ from those in the Indian Ocean in that they exploit a higher catch proportion from stocks subject to overfishing i.e. the BET stock, which is the stock the most subject to overfishing in the Atlantic Ocean. Overfishing of YFT and BET is intensifying in the Indian Ocean and characterizes the current situation, whereas for YFT the fishing pressure in the Atlantic has remained stable for over ten years and the harvested biomass is close to the MSY management objective. Our results characterise fleet exploitation at MSY, considered as a guarantee of sustainable catches for the fleets. Moreover, stock assessments do not consider the potential impact of global warming on tuna resources or the marine ecosystems that support tuna fisheries (Marsac, 2018). Compared with small-scale fisheries, industrial ones are sometimes considered less vulnerable to the impact of climate change thanks to their adaptive capacities with regard to fishing area, fishing technologies or market conditions. But on the other hand, artisanal fisheries can demonstrate very strong adaptability due to their ability to change fishing gear and target species (Green et al., 2021; Monnier et al., 2020). Thus, indicators of the vulnerability of fishing fleets and their economy to climate change are necessary to complete the present approach (Tokunaga et al., 2022; Belhabib et al., 2016).

The fishing gears show different ecosystem performances in relation to catch criteria, including the mature catch rate, bycatch TL mean and sensitive species catch rate. The mature catch indicator is associated with selectivity concerning juvenile tuna (i.e. greater protection of juveniles), with direct repercussions for the potential total catch and future spawning biomass (Perez et al., 2022). For a given fishing pressure (including the current estimate of Fmsy) or a given catch, the more juveniles are protected, the less the total impact on the biomass of the exploited stock (Beverton and Holt, 1957; Froese, 2004; Froese et al., 2016). Purse seine fishing on FAD induces higher BET and YFT juvenile catch, thus larger potential impact on the stock biomass, particularly on BET (Dagorn et al., 2013). In addition, the high fishing pressure on BET stocks could be a consequence of FAD fishing (Perez et al., 2022). Owing to the substantially smaller stock size of BET compared with YFT, the impact of catches using purse seines with FADs on the BET stock is markedly more serious than on skipjack or yellowfin stocks (Guillotreau et al., 2017). As adult individuals of bigeye tuna constitute the primary target for longliners in tropical waters, the development of juvenile catches on FAD have significantly compromised the longline fishery in two ways: reduction of spawning stock biomass (SSB) and a decrease in MSY (Miyake et al., 2004; Ovando et al., 2021). This outcome highlights an issue regarding the economic sustainability of longliners in the face of increasing of FAD fishing.

The performance of longliners on tropical tuna stocks (i.e. high mature tuna rate) is counterbalanced by their impact on the ecosystem due to their higher catch rate of sensitive species and a higher trophic level (TL) of bycatch. Sensitive species, such as sharks and rays, have a high TL. Longline and gillnet fisheries are the gears principally implicated in this problem and have been studied to develop mitigation methods for the reduction of sensitive species bycatch (Cortés et al., 2010; Shelley et al., 2014; Anderson et al., 2020), and to improve post-release survival rates (Gilman, 2011; Hutchinson et al., 2015). A low species-based selectivity is an issue for the marine ecosystem when the post-release survival rate of species is low and the trophic level high, as for gillnet and longline fisheries (Kiszka et al. 2021; Cortés et al. 2010), but maybe less for FAD fishing (Forget et al. 2015; Escalle et al. 2015; Eddy et al., 2016). Our results show variable longliner ecosystem performances, which could be due to variability in the pelagic longline *métier* (Swimmer et al. 2020). To better assess the ecosystem impact of fishing fleets, post-release survival rate by species, fishing gear and *métier* should be considered and assessed by RFMOs. Finally, we must highlight that our ecosystem impact indicator is highly conservative as based on the species selectivity only while this impact should in priority consider whether the resource-gear interactions lead to fishing mortality or not. In this context, another indicator allowing to assess the fishing mortality on ETP should be developed.

According to our results, purse seiners would have on average a similar ecological impact or would perform better than baitboats, which seems unlikely according to the literature (Gilman et al., 2020). The use of FADs by purse seiners have clear ecosystem impacts compared with pole-and-line and purse seine fisheries operating on free schools, in terms of interactions with endangered, threatened or protected (ETP) species as well as bycatch and discards (Amandè et al., 2017; Miller et al., 2017; Murua et al., 2021). Indeed, species-based selectivity of a FAD set in the Atlantic and Indian Oceans is near to 92.5 and 97% respectively (Murua et al. 2021). In the Atlantic Ocean, 87 ± 6% of all purse seiners bycatch, in average on the 2010 – 2016 period, is caused by FAD fishing (Ruiz-Gondra et al., 2017). Thus, a high species-based selectivity, and so a low discard rate was, expected for purse seiner fleets with a high FSC fishing rate which is not the case. Thus, a similar ecological performance among purse seiners (mostly using FADs) and baitboats suggest or confirm that bycatches (including ETP species) and discards are not yet well reported in the databases (Capello et al., 2023; Gilman et al., 2017; Herrera and Pierre, 2010) or estimated with a low level of both human or electronic observer coverage. Since the 2010s, observer data have been collected under the EU Data Collection Framework (DCF) and national voluntary programs, e.g. the OCUP program for French vessels, which reached a coverage rate of 100% in the Atlantic Ocean in 2015 and one over 80%, in the Indian Ocean since 2016. However, data from national programs are not considered by ICCAT and IOTC as public data while they would permit to improve the reliability of bycatch-based indicators of the sustainability ecological dimension of the fishery sustainability.

In addition to bycatch and discard data, discard mortality by species group (e.g. ISSCAP species groups) and fishing gears is still unknown (Eddy et al., 2016) while it represents an essential information to assess the right fishing mortality particularly for sensitive species. Moreover, both baitboat and longliner have an indirect impact on live-bait resources and marine ecosystems, which is not considered in RFMOs data and in this study but could be considered as supplementary bycatch species (Gilman et al. 2020; Litaay et al. 2021).

Another aspect of FADs is that a large percentage of drifting fish aggregating devices eventually drift beyond the fishing grounds, later potentially threatening sensitive areas via stranding (often referred to in the literature as 'beaching' - Imzilen et al., 2021), contributing to ghost fishing due to the one under the drifting FAD – recent progress should be highlighted on this aspect (Escalle et al., 2023) – and ultimately to the non-biodegradable and specifically plastic waste in the world's oceans. Such additional impacts of FADs should also be considered. This contrast, resulting from a difference in fishing mode, suggests that FSC and FAD fishing should be considered as distinct purse seine *métiers* in RFMO data collection (Imzilen et al., 2022).

3.4.2. Climate impact of tropical tuna fishing gears

In our analysis, the economic performance of EU purse seine fisheries is linked to ecological performances through fuel consumption. Fuel consumption is an indirect indicator of fisheries' impact on climate change and is also their primary expense reported to account for 35–75% of tuna purse seine fleet annual costs (Parker et al., 2015). The FUI gives information on fuel consumption by weight of tuna. In the literature, the FUI of fleets depends on the fishing gear used. Specifically, small pelagic gears have a range of 0.1–0.3 L.kg-1, gillnetters remain below 0.8–1 L.kg-1, longliners and baitboats range from 0.9 to 1.5 L.kg-1 (i.e. hook and line gear type), while bottom trawls range from 1 to 3.5 L.kg-1 (Parker and Tyedmers, 2015). Consequently, purse seiners have better performance in terms of a climate indicator (i.e. lower FUI) compared with other fishing gears (Parker et al., 2018; Parker and Tyedmers, 2015).

Our results reveal a contrast between French and Spanish fleets, with lower FUI observed for the French fleets (Atlantic: 0.50 L.kg-1; Indian 0.48 L.kg-1) compared with the Spanish fleets (Atlantic 0.56 L.kg-1; Indian 0.57 L.kg-1). In the literature, FUI is linked to fishing mode, characterising FADs as fuel-saving tools by that enhance catch rates while reducing search time (Dagorn et al., 2013; Scott and Lopez, 2014). In our results and in the literature, French fleets have higher FSC fishing strategy rate. Therefore, French fleets should have a higher FUI than Spanish fleets, which is not the case. Although the difference between these flags is low relative to variability caused by different gears, this contradiction is interesting. Recent studies have proposed a contrary effect of FADs in the Indian Ocean, probably leading to consistent distances travelled between FADs, but ultimately lower catches than on FSC (Chassot et al., 2021; Basurko et al., 2022; Tolotti et al., 2022). These conclusions are consistent with our results but should be considered with caution because fuel consumption is influenced by the skipper's choice to make sets on FADs or FSC, depending on the information available, and efficiency optimisation (Basurko et al. 2022). However, comparable results using another fuel consumption data source would be interesting because our dataset might be biased due to the fact that diesel loads at sea may not be taken into account (Anom. Pers. Comm. 2024). Assuming this trend and considering the impact on stocks and ecosystems, FSC fishing could emerge as a fishing mode with a higher ecological performance than other tropical fishing gears and métiers (i.e., increased catch of mature tuna, reduced bycatch of sensitive species, and perhaps a lower FUI).

3.4.3. Energy efficiency of European purse seiners

In total, fishing on FAD rather than FSC induces larger ecological impacts (e.g. on juveniles, bycatch and sensitives species), while improving some economic performances of the fleet (e.g. total catch, net profit). In contrast, to avoid a potential conflict between ecology and economy of European purse seiners performances, a higher FSC fishing rate should lead to higher economic and socio-economic performances. In fact, demonstrating such a conflict is difficult because observation needed to assess the direct ecological impact by fishing strategy is currently not available in the RFMO's database.

However, our analysis on economic and socio-economic indicators from 2009 to 2019 reveals that the economic sustainability is linked to a high energy efficiency, tuna price and catches on FADs. However, such a result does not consider the potential adverse effect on FAD use on both the stock status and the ecosystem health. Energy efficiency provides information on the monetary value generated per litre of fuel consumed. In the short term, FAD use has a high set efficiency, i.e. high positive set rate, which leads to lower energy costs, as supposed by

Basurko et al., (2022). But in the long term, decrease in stock abundance and MSY may jeopardise such result (Ovando et al., 2021).

The short-term economic performances of EU purse seine fleets (i.e. higher RoFTA, margin rate, net profit and work productivity) correspond to lower energy costs and higher energy efficiency, as supported by the literature (Cheilari et al., 2013; Parker et al., 2015). High economic performances of EU purse seiners were observed in the 2012–2013 and 2017–2019 periods when the world tuna price was high (Guillotreau et al. 2022). The dependance of the economic health of purse seiners on the tuna market is well knew and studies: given the high volatility of YFT prices, changes in tuna prices are not passed on to consumers but absorbed by the fleets, which must still meet the growing demand for catches, primarily facilitated by using FADs (Lecomte et al., 2017; Guillotreau et al., 2022; Miyake et al., 2004). In this context of the global tuna market and condition of the major tuna stocks (YFT in the Indian Ocean and BET in the Atlantic Ocean) a trade-off between FAD and FSC fishing is reached to satisfy one of the main targets of Sustainable Development Goal No.14, however this trade-off still ignores the long-term effects on tuna stocks (Ovando et al., 2021).

3.4.4. Social performance of European purse seiners

Concerning the socio-economic dimension, our analysis shows a higher social performance of the French fleets, as these provide stable FTEs with a higher average fisher salary costs. For each ocean, the French fleet created less FTEs, indicative of lower turnover, than the Spanish fleets. Inter-annual variability of tuna catches is often considered as a socio-economic indicator, as constant catch opportunities are normally preferred by the industry and provide constant job opportunities (FAO, 2022). Our analysis does not, however, demonstrate this link for EU purse seine fleets. The average fisher salary cost is linked to FSC fishing rate which is probably a consequence of their joint participation in describing nations. The remuneration structure for fishers varies among companies. French companies use a fixed wage system and a share of the catch per ton (not indexed to the price of tuna), while Spanish companies only propose a share of the catch per ton (Maufroy, Com. Pers.). More information on the nature of FTE contracts (short- or long-term) is needed to draw conclusions on the social performance of fleets for fishers. The working conditions of fishers and their social cover remain insufficiently investigated. A recent anthropological study of the use of FADs by fishers reveals the transformation of the profession from, in their words, a 'hunting' activity to a 'gathering' activity (Reyes and Airaud, 2022). A distant-water fleet with individuals of several nationalities on board poses challenges for assessing social inequality and human rights aspects (Belhabib and Le Billon, 2022).

3.4.5. Perspectives

Our results on European purse seiner fleet performances compared with other tropical tuna fisheries raise questions about how to better assess economic and ecological performances to improve fisheries sustainability. Data on discards and landings by species, fuel consumption and social data by fishing fleet and fishing métiers are still needed to directly compare fisheries sustainability performances. Indicators on waste pollution such as plastic could also improve fishing fleets comparison and potentially distinguish purse seiners and baitboats (Guillotreau, et al. 2023). For the purse seine fishery assessing direct sustainability performance of different fishing mode is difficult because there are deployed during a same fishing trip and cannot be disentangled (e.g. in the case of FSC and FAD strategies of purse seiners) (Basurko et al., 2022).

The dashboard of indicators proposed in this study can be used to analyse the effect of fisheries management decisions (Capello et al., 2023). Currently, the main management tools considered to limit FAD fishing are restrictions on the number of FADs (Kaplan et al. 2014; Perez et al. 2022) and implementation of multiple time-area drifting FAD fishing moratoria (Goujon and Labaisse-Boclilis, 1999; ICCAT 1998). Comparing indicators between in and out time-area drifting FAD fishing moratoria could be an interesting direction for future research to quantify the impact of FAD fishing, e.g. on ecosystem indicators, fuel use intensity or economic indicators.

The last moratorium implemented in the Atlantic Ocean was considered effective for YFT and SKJ stocks, but no conclusion could be drawn for BET (Perez et al., 2022). In this study the juvenile fishing rate considered average juveniles for the three species SKJ, BET and YFT. However, considering FAD use impact on YFT and BET juveniles, an operating diagram indicator of the purse seine métier should consider only the juvenile rate of these species. During our study period, the IOTC implemented an alternative or complementary management strategy by introducing a total allowable catch (TAC) of YFT since 2017 (IOTC, 2016). In turn, the purse seine fishing companies manage the quota throughout the year by using more FADs (catching few YFT but more SKJ in terms of weight) than before the quota system was set up (Tolotti et al., 2022). For the authors, this rebound effect raises questions about TAC adjustment, that could differentiate adult tuna TAC from juvenile tuna TAC. A dashboard approach could provide information on sustainability performance before and after TAC implementation. In our study, species-based selectivity in the Indian Ocean decreased after this implementation but further studies are needed. More generally, RFMOs should improve data collection quality (i.e. species-based selectivity, discards, catch and, fuel consumption, but also economic and social data), use a dashboard approach to improve monitoring of their tropical tuna fishing fleets' sustainability and assess their Sustainable Development Goal achievements.

Finally, assuming an increase in the number of environmentally concerned consumers, improved practices towards more FSC fishing could be very positive for the sector. Environmental non-governmental organisations are calling for a distinction in trade between canned tuna from FADs, considered unsustainable, and canned tuna from non-FAD fishing practices, considered more sustainable (Failler et al. 2014). The sustainability movement (ecolabelling and voluntary commitment) could encourage stakeholders to adopt more sustainable fishing strategies to meet the current high demand, with higher profitability, but this effect remains limited (Froese and Proelss, 2012; Potts et al., 2016; Martin et al., 2012). Recently, the Marine Stewardship Council's fisheries standards has evolved (V.3.0) requesting non-entangling and biodegradable FAD use but still allows certification of tuna caught under FADs because it is impossible to differentiate fish caught under FAD or FSC in purse seine wells with a high degree of certainty (Lyons, 2022). A time FAD moratorium would allow this distinction. However, it remains to be analysed to what extent these market-based incentives are effective in moving tuna fisheries towards greater sustainability (Guillotreau et al., 2023).

3.5. Conclusion

This study analysed the sustainability performances of European tropical tuna purse seine fisheries and ecological performances of tropical tuna fisheries in the Atlantic and Indian Oceans using a dashboard approach. This dashboard is a concrete application for fishing fleet case studies and offers potential added value for the management of well documented fishing fleets. A PCA approach was conducted to compare sustainability performance between gears, fishing area and years. Purse seiners and baitboats show better ecological performances than longliners and gillnetters in terms of bycatch and catch of endangered, threatened, or protected species. However, purse seiners and baitboats catch more tuna juveniles than longliners and gillnetters, particularly on fishing aggregating device (FAD). To assess the impact of tuna fisheries on the marine ecosystem, the species-based selectivity and trophic level of bycatch indicators should be interpreted jointly.

Stock-based performance depends on species composition, tRFMO stock management (i.e. the ocean being fished) and should not be interpreted as a direct impact of fisheries on stocks. In the literature, purse seiners have better climate impact performance (in terms of fuel consumed per weight of tuna) than other fishing gears, but we could not consider this indicator in our fishing gears comparison analysis due to lack of fuel consumption data. Social and socio-economic data were not sufficient to compare fishing gears as well. As suggest in the literature, economic performances of European purse seine fleets are linked to their fishing mode (i.e. fishing rate on FADs). Also, in ecological terms, fishing on FSC should provide a better ecological result (including size-based and species-based selectivity). We demonstrated an important lack of catch data reporting by tRFMO, which can lead to outliers results as in the case of European purse seiners (their species-based selectivity were inconsistent with the literature using observer data). We found climate-impact performance to likely be better in purse seiners with a high FSC catch rate.

Finally, we want to ask whether, when economy meets ecology, it is truly conflicted? For the purse seiners, this is likely for a long-term perspective. We confirm that the global tuna market context induces European purse seiner short-term economy (annually) to be based on catch quantity, allowed by FAD use, rather catch quality (mature yellowfin and bigeye tuna). However, long-term economic performance indicators are needed. This fishery needs to reduce FAD fishing impact on tuna juveniles and biodiversity globally. To assess this impact, data on catch by species and fishing mode is needed. More widely, applying a dashboard method to various fisheries could yield insights into key dynamics, guiding research, and management efforts for enhanced sustainable fishing practices. Aware of this contradiction, the fishery sustainability framework should move away from short-term economic indicators and prioritise ecology and social indicators.

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4. Les stratégies des flottilles de pêche comptent dans l'évaluation de leurs performances environnementales. Vu par l'analyse de cycle de vie

For more sustainable tropical tuna, the fishing strategies and fishing fleet matter. A life cycle assessment approach.

Article en vue de publication dans la revue *Fisheries Research*

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Keywords

carbon-efficiency, energy-water-nexus, fishing aggregating devices, free school, carbon footprint, economic

Highlights

• The environmental impact of tropical tuna purse seine fisheries (EU-PS) is related to water and carbon footprint (energy-water-nexus)
• Tuna fished on a fishing aggregating device (FAD) has a higher carbon footprint than tuna fished on free school (FSC)
• Seine construction and salt used for the brine contribute to the water footprint (40 ± 14% and 25 ± 6%)
• The fuel consumption of purse seiners and their supply vessels contributes to the carbon footprint of EU-PS (90 ± 10% and 10 ± 10%)
• The Spanish fleet in the Atlantic Ocean has a higher carbon footprint than other fleets, probably caused by older vessels

Abstract

Seafood products meet a wide range of nutritional, economic and social needs. Face increasing seafood demand and growing environmental concerns, assessing the environmental impact of fisheries products and their economic and social performance has become a priority. Using European tropical tuna purse seine (EU-PS) fleets as a case study, we conduct an attributional life cycle assessment based on annually data (2015-2019). This study is an initial step before a routine parametrized LCA, which could monitor the global impact of fisheries products. The EU-PS used two fishing strategies, i.e. on free school (FSC) or on fishing aggregating devices (FAD). The fishing strategy has never been considered in an LCA study, even though FAD fishing is controversial, i.e., impact on marine ecosystems and on the reproductive capacity of tuna, waste of FAD raft, and stability of catch). The objective of this study is to identify the impact categories of interest for EU-PS, find out which parts of the life cycle most contribute to these impacts and does the impact differs depending on the fishing fleet (i.e. flag-ocean) and their fishing strategy (i.e. tuna fished on FAD or FSC).

Our main results show that major impact categories that fisheries research needs to consider are the climate change contribution (kg CO2eq.) and the water depletion (m3), in line with the energy-water-nexus theory. The fuel consumption of fishing and supply vessels is the first contributor to potential climate change impact (95%). The fishing gear and the salt

consumption for the brine are the major contributors to the water depletion potential (i.e., nylon and salt origin). Tuna fished on FSC has a smaller carbon footprint than tuna fished on FAD for all EU-PS fleets except for the Spanish fleet in the Indian Ocean. This fleet has a similar carbon footprint of its FSC tuna than its FAD tuna. However, this fleet maximizes its global carbon footprint in terms of services provided to tuna stocks (mature tuna fishing), business economy (net profit), and, more recently, the number of full-time equivalents (2018-2019). Further research on LCA methodology is needed to better quantify the impact of the end of life of FAD rafts on the marine environment, as plastic pollution, and compare these eco-efficiency results with other types of fishery (other gears or small-scale fisheries).

We conclude that FSC tuna is better for the climate than FAD tuna. Without a fishing effort report, reducing the supply vessel would improve the carbon impact of FAD tuna. Work on nylon and salt production is necessary to reduce the water footprint of EU-PS. Based on annually collected data, a life cycle assessment routine could provide an effective response to such comparisons and enable future improvements to inventory databases to be considered.

4.1. INTRODUCTION

Seafood is an essential part of many people's diets around the world, providing a higher source of protein and an ideal package of nutrients (C. Liu and Ralston 2021). Seafood promises nutritional needs at low climate impact compared to meets, but large variability exists, even within species groups and species, depending on production method (Bianchi et al. 2022). Many studies compare climate efficiency of seafood between species targeted and fishing gears (McKuin et al. 2021; A. Avadí and Fréon 2015; 2013; Gephart et al. 2021) or fleet segment (Laso et al. 2018; Á. Avadí, Vázquez-Rowe, and Fréon 2014) but any at flag or fishing strategies scale while a large variability in the performance of seafood products is due to a "skipper effect" (Piwońska 2021; Vázquez-Rowe and Tyedmers 2013). As the chemical environmental efficiency of fisheries is strongly linked to fuel consumption efficiency (Parker et al. 2018 ; Gaphart et al. 2021), LCA studies call to consider economic and social services for comparing fishing methods and so seafood products (Piwońska 2021). Assess a skipper effect need to collect data by vessels which can by time-consuming (Vázquez-Rowe and Tyedmers 2013) and make social and economic efficiency difficult to compare with other fleets (i.e. collect for one case study). New approaches using already collected data need to be developed to identify and monitor the most environmentally-friendly fishing practices and strategies, while keeping in mind our societies' economic and social needs.

<u>We propose to assess the ecologic, economic and social efficiency of European tropical tuna purse seiners fleets and their fishing strategies</u> to tradeoff between the resolution of declared data collection on fishing activities and socio-economic data, and the “skipper effect” exposed by Vázquez-Rowe and Tyedmers (2013). European tropical tuna purse seiners are an interesting case study because they are industrial fleets required to declare data on their fishing activities to tuna regional fisheries management organizations (RFMO) and annually declare socio-economic data to European Union (Scientific, Technical and Economic Committee for Fisheries - STECF) at a fleet resolution (Ougier et al. In prep).

The tuna and tuna-like catch represents around 5.5 million of tons (6% of world catches) and are one of the top four most valuable groups of species in 2020. The skipjack tuna (*Katsuwonus pelamis*) and yellowfin tuna (*Thunnus albacares*) represent more than 55 percent of catch of tunas and tuna-like species group (FAO, 2022). Tropical tuna fisheries have important economic and social roles providing a significant source of revenue, food security, nutrition (protein and omega 3) and income to millions of people (Peng et al. 2017, Liu et al. 2014 ; Chassot et al., 2019, McCluney et al., 2019, McKinney et al., 2020). Tunas are a low-cost source of protein for much of the world and provide employment in areas where fishing and processing are concentrated (McKinney et al. 2020). The industrial fishery is reported to contribute approximately 50% of the Indian Ocean’s tuna catches (Artetxe-Arrate et al., 2021) and the major contributor of catch data in the Atlantic Ocean (Monin et al. 2017), demonstrating the important role the sector play. The purse seine gear is dominant in catch, and the main industrial purse seine tropical tuna fleets are the French and Spanish in both Atlantic and Indian oceans (Coulter et al. 2020). The pelagic fisheries are among the least impacting in terms of energy efficiency (Parker et al. 2018 ; Gaphart et al. 2021), with low fuel consumption by landed fish weight compared with bottom fishing (e.g., trawling). Purse seine tuna fisheries have a significant impact on pelagic ecosystems due to the different fishing strategies used (catch on free schooling-FSC or catch on free school associated with an object). The presence of an object allows aggregation of pelagic fishes and reduce time of searching (Dagorn et al. 2013). There are considered two different strategies because of a significant difference of target species and size. Free-schooling is principally composed of mature yellowfin and bigeye tunas, schooling associated with an object are composed of mature skipjack tuna, juvenile of yellowfin and bigeye tuna. Different type of objects exists depending on their origin (natural or artificial) and their type (anchored or drifting). Tropical tuna purse seiners commonly fish on drifting artificial object named Fishing Aggregating Devices (FAD) (Maufroy et al. 2017). FAD fishing causes a high proportion of bycatch with sensitives species catch which are important for the pelagic ecosystem (high trophic levels such as sharks). FAD fishing has an impact on the tuna stocks' sustainability because it leads to the fishing of large quantities of immature bigeye and yellowfin tuna (Artetxe-Arrate et al., 2021 ; Artill et al., 2012 ; Murua et al., 2021 ; Dagorn et al., 2013). Tuna RFMOs (ICCAT & IOTC) have promoted the reduction of FAD use in the last decade (IOTC Resolutions 15/08, 16/01, 17/08 ; ICCAT Recommendations 98/01, 15/01) and more recently the research and progressive replacement of existing drifting FADs by non-entangling biodegradable FADs (bioFADs) to mitigate ghost fishing (Murua et al. 2023).

Peer-review studies have already interested in fuel consumption and ecosystem impact differences between FAD and FSC strategies (Dagorn et al. 2013; Basurko, et al. 2022; Murua et al. 2021) or between tropical tuna fishing fleets (Ougier et al. 2024) but these studies do not approach other potential chemical environmental impacts as acidification, eutrophication potentials or water and plastic use at strategies scale. In addition, studies on differences of fuel consumption by fishing strategies do not consider fuel consumption of supply vessels used for FAD strategy (Arrizabalaga and De Molina 2001) while fuel consumption of a supply vessel is estimated at 15% of a purse seiner (Chassot et al. 2021). In their report, Zudaire et al. (2020) compare the environmental impacts of different drifting FAD structures used by tropical purse seiners but do not estimate how much the FAD structure contributes to the total purse seiner environmental impact.

Life Cycle Assessment (LCA) is an ISO-14000 standardized method (ISO (The International Organization for Standardization), 2006a, 2006b) to estimate potential environmental impacts. The LCA commonly used for food production and seafood production (Pelletier and Tyedmers 2008; A. Avadí and Fréon 2013; Ruiz-Salmón et al. 2021; Abdou et al. 2018; Vázquez-Rowe et al. 2010). LCA assesses potential environmental impacts associated with a product or service by compiling an inventory of inputs (resources required) and outputs (pollutants emitted) throughout the entire life cycle of the product, "from cradle-to-grave", i.e. from the extraction of raw materials, through production, construction, use, and when appropriate, waste management and disposal or recycling (Consoli et al., 1993; Guinée et al., 2002). Hospido and Tyedmers (2005) assessed the LCA impact of frozen tuna from Spanish fleets in Atlantic, Indian and Pacific Oceans as due to diesel production, diesel combustion, anti-fouling paint use and marine transport of carcasses. FAD raft, vessel supply contribution to this impact, and more widely difference of environmental impact by fishing strategy, remains unknown.

The environmental impacts of products (i.e. kg of landed tuna) have become of increasing concern to governments, private and public organizations as well as the general public which are also concerned by economic and social issues (Vásquez-Ibarra et al. 2020; WBCSD 2006; Rybaczewska-Błażejowska and Masternak-Janus 2018). The eco-efficiency notion is defined as "the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle, to a level at least in line with the earth's estimated carrying capacity" or more generally "to do more with less" (Schmidheiny and Stigson 2000). Usually, the eco-efficiency in fisheries case-studies refers to fuel use intensity as principal source of impact of fisheries (Hospido and Tyedmers 2005; A. Avadí and Fréon 2013; Ramos et al. 2011; Vázquez-Rowe et al. 2011; González-García et al. 2015) but remains under-research in fisheries (Piwońska 2021). Few studies assess eco-efficiency (impacts on climate - kgCO2) in regards to economic benefits (catch value – Vázquez-Rowe et al. (2010); (2011)), bycatch or landed protein (McKuin et al. 2021). For now, eco-efficiency indicators disregard relevant biodiversity parameters. Efforts are needed to include biological aspects in fishery related ecoefficiency studies (Piwońska 2021; Ramos et al. 2011).

We propose to construct an average LCA of EU-PS fleets in Atlantic and Indian ocean on recent years (2015-2019) and their strategies (FSC/FAD) based on annually collected data and compare LCA results with other food products. Then we propose to compare eco-efficiency of fishing fleets relatively to their performance for tuna stocks, economic rentability and job provider. The objective is to answer the following questions:

.What are the principal environmental impacts of purse seiners tuna product comparing to the other seafood products? .How much a drifting FAD raft contribute to the total environmental impact of a tropical tuna?

.Do the four European purse seiner fleets (EU-PS) have similar environmental impact patterns?

.Is the fishing strategy of fishing fleet a relevant criterion for assessing the environmental impact of tropical tuna? Which strategy has the least impact?

.Which fishing fleets is the most eco-efficient?

4.2. MATERIALS AND METHODS

4.2.1. Goal and scope definition

Conventional LCA consists of four phases (ISO standard 14040): goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation (Figure 4.1). The goal of this LCA study is to assess the environmental impacts associated with the fishing activity of European tropical tuna landings by the Spanish and French purse seiner fleets. A purse seine fishing fleet corresponds to a group of fishing vessels flying the same flag (French or Spanish flag) as well as auxiliary fishing vessels, which may have a different flag.

The study objective is to better understand how impact life cycle assessment (ILCA) at fleet scale can be useful for a tropical tuna fisheries management.

Tropical tuna purse seine fisheries are pelagic fisheries providing frozen tuna. The scope of the study covers the activity of fishing fleets and impacts associated, which ends with the landing of the frozen tuna. The landed ports are in Abidjan (Ivory) and Port-Victoria (Seychelles) for Atlantic and Indian ocean. The tropical tuna purse seiner fleets provide three major tropical tuna species which are Yellowfin (*Thunnus albacares* – YFT), Bigeye (*Thunnus obesus* – BET), Skipjack (*Katsuwonus pelamis* – SKJ). The functional unit (FU) considered is 1 kg of landed tropical major tuna by European purse seining vessels in one year of operation (2015-2019 in average), reflecting the function of delivering raw material for further processing in local canning industries. Fishing fleets can have other important function as compagnies which are net profit and full time equivalent. The number of full time equivalent of the four fleets by year coming from AER. The net profit corresponds to landings incomes in value less total costs (i.e. energy, fixed, no fixed, repair, maintenance and salary costs) and it is calculated based on STECF data, as proposed by Ougier et al. (In prep) (cf. 2.).

Even if purse seine fisheries are known as the least carbon footprint fishery method, tuna tropical purse seiners can have ecosystem and tuna species impacts, notably using FAD (c.f. 2.), which is important to consider. We compare the eco-efficiency of one kilogram (kg) of tropical tuna changing the functional unit, such as associated weight of bycatch and juvenile tunas. Tropical tuna fisheries provide other economic and social services. We propose to compare tropical tuna economic and social services, e.g., net profit and full-time equivalent provided by fishing activities, divided by the impact of the LCA assessment. In other words, we look at which fishing practices provide the greatest economic and social return on their impact in accordance with the principle to "do more with less" (**Schmidheiny and Stigson 2000**).

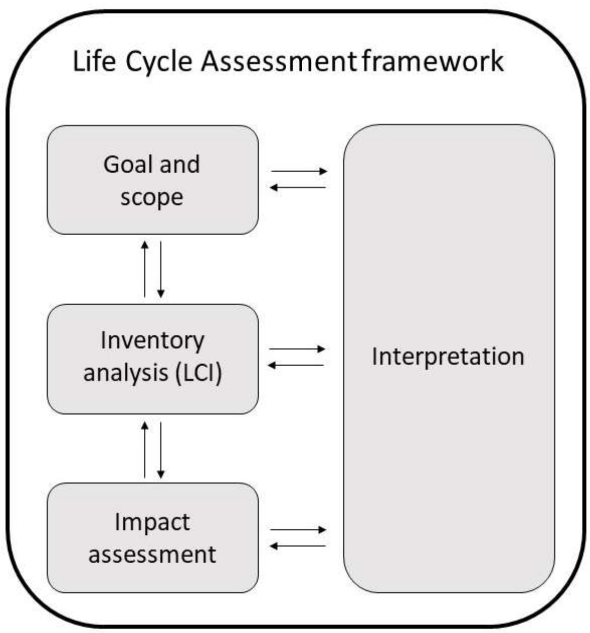

Figure 4.1: Life cycle assessment framework scheme (ISO 14040)

4.2.2. System boundaries

The system under study comprised the phases of a vessel's life cycle: construction, use, maintenance and end of life (EoL), including hull and engine production, diesel, salt consumption, antifouling, lubricant oil emissions, fishing gears (seines, FAD raft, boys) and boat paint production (Figure 4.2). Crew impact was limited to the emissions of the airplane travel, excluding provision of food and waste considered negligible (**Hospido and Tyedmers 2005**). This assessment constituted a so-called cradle-to-gate study for the product (i.e., landed tropical tuna) and a cradle-to-grave study for the main carrier of the fishing operations: the fishing vessels and associated supply vessels (**Guinée et al. 2001**). Landing operations at port were excluded from the system boundary (see Figure 4.2), as well as a series of biological issues, such as seafloor use, as we assume it is not supposed to be a matter of fleet management but of territorial policies.

These fleets target major tropical tuna using two type of strategies: on Free School (FSC) and on Fishing Aggregating Device (FAD). We provide impact assessment result by landed tropical tuna catch on both strategy (FSC or FAD) based on weight data.

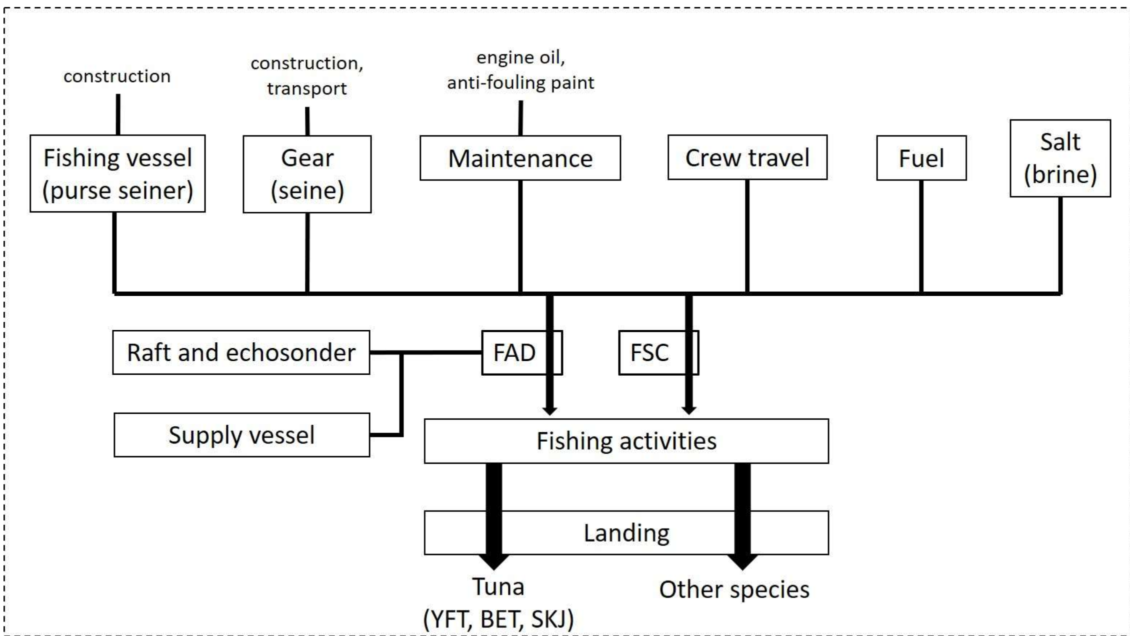

Figure 4.2: Block diagram of the system studied. Dotted line represents the system boundaries. Black arrows are inventory flows.

4.2.3. Allocation to environmental impacts

Purse seiner vessels can apply both strategies in the same time (i.e. searching FSC of tuna and traveling to the next FAD buoy). The allocation of impact of purse seiners activity is based on fishing effort done one FSC or FAD. The fishing effort unit is the number of sets done on each strategy, considering positive and null (without catch) sets. We use data of the French Observatory of exploited pelagic ecosystems (Ob7, IRD) and the Spanish Oceanography Institute (IEO) provided by anonymised vessels, year and ocean. The impact of supply vessels activities (i.e. repair and maintenance of FAD raft), raft and echosounder construction are fully allocated to FAD landed tropical tuna.

We do not apply a co-product allocation (i.e. landed non-targeted species on local market - as tuna-like species, bony fishes and billfishes) because they represent a low percentage of tropical tuna purse seiners catches (1.2% - Amandè et al. 2017 ; 3.3% - Juan-Jordá et al. 2018) and have an economic value that is still poorly understood (Amandè et al. 2017), especially in Indian Ocean.

4.2.4. Data acquisition and Life Cycle Inventory (LCI)

4.2.4.1. Primary data

We calculate an average impact assessment of European tropical tuna fishing fleets in Atlantic and Indian Oceans on a recent period (2015-2019). For reasons of confidentiality, catch public data in both ocean (Atlantic Ocean – ICCAT https://www.iccat.int; Indian Ocean – IOTC https://iotc.org) are only available at fleet level and is therefore aggregated for a set of vessels.

The amount of active fishing vessels by year and ocean is provide by tuna RFMOs. For tRFMOs, an active fishing vessel is a vessel allowed to fish however not all of them actually fish (pers. com. E. Chassot). The number of active vessels for each fleet and year have been established from active vessels list of RFMOs corrected with global fishing watch website (https://globalfishingwatch.org) which makes public the VMS tracks of fishing vessels and their supply. The number of vessels (purse seiners and supply) and catch data by fleet by year are detailed in supplementary material 3.1.

Quantity of vessels construction materials (i.e. steel, IT equipment, fridge parts) and maintenance consumptions (i.e. anti-fouling paints, engine oil, etc.) have been calculated based on inventory data collected during the ICV-Fish project (then implemented in the AGRYBALYSE© database). ICV-Fish project provide inventory data of different size-scale of purse seiner fleets fishing Atlantic tropical tuna (four purse seiners - PS), Mediterranean bluefin tuna (seven PS), European anchovy (six PS), European pilchard in the bay of Biscay (thirteen PS) and European pilchard in the east coast Atlantic (ECA) (two PS) (Cloâtre 2018). Previous studies estimate that quantity of materials for vessels constructions is correlated with the length of vessels (Hospido and Tyedmers 2005). Based on inventory data on these 32 PS from AGRIBALYSE©, we calculated linear function between quantity of materials and length of the vessel.

We calculate the average length of fishing vessels (PS) and supply (SV) for the 4 European purse seiners fleets (French and Spanish fleets in Atlantic and Indian oceans). We can estimate the quantity of materials needed to build them using the linear function between quantity of materials and length of the vessel.

All equipment or materials are not used for all type of purse seiners because of different needs (fishing conditions). This linear model is not pertinent for the following materials – batteries, navigating equipment, wood- which can be identify with a plateau effect above a certain vessel size. For these cases, we use the average quantity of the 4 Atlantic tropical purse seiners of the ICV-Fish project as the best proxy for the 4 fleets of interest.

The end-of-life is not considered. Little information is available on the actual end-of-life of ships as these vessels are often resold to several other fleets before being supposed dismantled (Pers. Com. A. Fonteneau). Hospido and Tyedmers (2005) indicates that this part of the life cycle is negligible. Because of this lack of information, we apply the same average life span of purse seiners to each fleet (thirty-five years). Life span of vessels should not be confused with the length of time they are used by fleets. From our point of view, it would be misleading to allocate the total impact of a ship's construction solely to one of its many owners. We apply a lifespan of thirty-five years for fishing vessels and their supply, which is classically applied in the literature (Hospido and Tyedmers 2005).

The fuel consumption of fisheries is a major impact source (Hospido and Tyedmers 2005; A. Avadí and Fréon 2013; Ramos et al. 2011; Vázquez-Rowe et al. 2011; González-García et al. 2015). Rather than using seiner consumption data from Agribalyse©, we use the model of fuel consumption of Indian tropical tuna purse seiners of Chassot et al. (2020) to better estimate the fuel consumption of the four European purse seiner fishing fleets. The model uses as parameters the vessel length, the construction period, the number of days at sea and the number of sets done on FSC and FAD. The Chassot et al. (2020)'s model was calibrated on industrial purse seiners (>70m of length) in Indian ocean. Basurko et al. (2020) explain that fuel consumption of purse seiners is correlated to the distance travelled by day (r = 0.99). However, the distance travelled by day is non-explicit in the model of Chassot et al. (2020). This information is contained in the days at sea (DAS) parameter. We conducted a preliminary analysis on distance travelled by day of French purse seiners vessels, calculated from VMS data position data of the French Observatory of exploited pelagic ecosystems (Ob7, IRD). We observed a higher distance travelled by day in Indian ocean than in Atlantic Ocean (264 ± 34 and 238 ± 9 km.day^{-1} in average respectively) with a disparity between years (Sup. mat. 3.2). Apply the model of Chassot et al. (2020) without correction could overestimate fuel consumption in Atlantic Ocean. We calculate a correction factor applied on DAS number of vessels in Atlantic Ocean before apply fuel consumption model (Equation 3; Table 4.2). Data used to apply the Chassot et al. (2020)'s model come from French and Spanish observatory (Ob7, IRD and IEO).

$$\text{Equation 3}: DAS\ ATL_{y,f} = DAS\ ATL_{y,f} * \left({}^{Dis\ ATL_{y,d}}/_{Dis\ IND_{y,d}} \right)$$

With DAS: days at sea, ATL: Atlantic Ocean, IND: Indian Ocean, Dis: Average distance (km), y: year, f: fleet and d: day

Table 4.1 : Correction factor applied on Atlantic days at sea number (DAS)

Year	Correction factor: ${}^{Dis\ ATL_{y,d}}/_{Dis\ IND_{y,d}}$
2015	78 %
2016	94.3 %
2017	90.9 %
2018	92.3 %
2019	99.5 %

Chassot et al. (2020) provide fuel consumption data of supply vessels of European fleets in the Indian ocean from 2015 to 2019 (any model can be produced because of a lack of bunkering data). We calculate a percentage of purse seiners consumption reported to purse seiners. We estimate the supply vessel consumption as 15.3% ± 1.5 of a PS on average. We apply this percentage to each purse seiner fuel consumption estimation (Mat. Sup. 3.3).

The salt consumption of European purse seiners (used for the brine) is calculated based on salt consumption (kg of salt. catch of tuna in tons^{-1}) of the tropical tuna fleet of the "Compagnie Française du Thon Océanique" (CFTO - https://www.cfto.fr). The salt consumption estimate is 97 ± 25 kg.ton^{-1} over the period 2015 to 2019 and we assume that brine is completely discharged into the sea after use. In the literature, the salt impact is linked to salt creation (Althaus 2007).

The fishing gear modelling is based on the ICV-Fish project inventory (Agribalyse©), which propose a purse seine of dimension 1600m x 220m for Atlantic purse seiners, and 1800m x 250m for Indian purse seiners respectively made up of 58T and 70T of nylon, 29T and 35T of steel and 5T and 9T of ethylene vinyl acetate (EVA) for floats. Indeed, purse seines don't have similar dimensions between ocean because the thermocline (preventing tuna from diving during a fishing set) is not at the same depth in the two oceans (up to 100 m in the Atlantic and 300 m in the Indian).

Imzilen et al. (2021) provides the annual number of new buoys deployed by the French and associated flags purse seine fleets in the Atlantic and Indian oceans over the period 2008-2017. With the collaboration of T. Imzilen, the number of new echosounder buoys launched each year by each fleet was updated to 2019. We calculate a number of average new buoys deployed by vessels, by dividing the Imzilen et al. (2021)'s result by the number of vessels in each fleet (Table 4.1). As we were unable to obtain additional data on the number of buoys deployed per year by Spanish fleets in the Atlantic and Indian Oceans, we assume that Spanish fleets launch the same number of buoys per purse seiner vessels as the French in the same ocean. However, it should be noted than Spanish fleets used more boys during first years of the present study (Com. Pers. L. Dagorn, IRD). Generally, buoys recovered by vessels end up in "buoy cemeteries" located in ports. Buoys may be recovered by the shipowners or dismantled for reuse locally, but there is no data to quantify this (Com. Pers. P. Cauquil, IRD). We assume the end-of-life of echosounder buoys as electronic waste processed on land.

FAD rafts are difficult to follow as they do not have their one GPS mark. Fishermen can deploy echosounder buoys on a new raft or on a found raft launched by another flotilla, and so may be deployed several times in its lifetime on several different rafts. This complexity makes it difficult to know the exact number of new rafts launched each year by a fishing fleet. We assume that the number of new rafts launched corresponds to the number of new echo-sounder buoys launched (Imzilen et al. 2021, 2023). There is no estimation of the number of

FAD raft lost at sea in the Atlantic and Indian Oceans however, Escalle et al. (2020) estimated that more than 90% of FADs are never recovered after deployment in the Pacific Ocean. We assume the end-of-life of FAD raft as fully waste in the marine environment. The BioFAD project (2017-2019) proposed a first ILCA of FAD rafts deployed by European purse seiners. For our study, we assume homogeneous FAD rafts corresponding to the conventional raft detailed in the BioFAD project (NE FAD _1 "conventional") which was the most used by European seiners over the period (2015-2017) (Zudaire et al. 2021). This conventional raft is composed of a metallic structure without tuna net. In Atlantic Ocean, the deep counter-current (Guinea current) limits the drift of rafts towards the west available with a higher attractive rope (Com. Pers. M. Capello; Imzilen et al. 2021). We choose to modelized an attractive rope with a different height in both Atlantic and Indian ocean, of 90 m and 60 m respectively (Com. Pers. M. Capello).

To estimate the travel impact of the crew in fly, we firstly estimate the number of fishermen on board. Based on the construction characteristics of purse seiners of Piriou compagnie available on their website (https://www.piriou.com; Sup. Mat. 3.4.a.), we calculate the maximum number of people that can be accommodated on board, depending on the length of the vessel (ten purse seiner plans consulted, from 36m to 90m of length). With a linear function (Sup. Mat. 3.4.b.), we can deduce a theoretical number of crew on board for each vessel (purse seiners and supply) for the four fleets of interest (Table 4.1). We assume that the number of fishermen on board is the maximal capacity of the vessel. There are several nationalities on board in different proportions depending on the fleet. In concertation with professional organizations (ORTHONGEL, CFTO), we assume that 50% of the crew are national officers (French of Spanish) in both Atlantic and Indian Oceans with a turnover of two (i.e. 2 round trips per year). The others members of the crew are composed of 50% from Ivorians (Abidjan) and 50% of Malagasy (Ivato) in Indian Ocean and composed of 100% of Ivorians (Abidjan) in Atlantic Ocean. Ivorians and Malagasy crew has a turnover of one (i.e. 1 round trip per year). Thanks to a fly distance travel tool online (https://fr.distance.to), we estimate distances in fly between capitals and fishing ports: Paris (France) – Mahé (Seychelles): 7840 km, Paris - Abidjan (Ivory): 4885 km, Abidjan – Seychelles: 6695 km and Ivato (Madagascar) – Seychelles: 1980 km.

Table 4.2 Average Fleet characteristics – data for a type vessel of each fleet

Characteristic of a typical vessel of the fleet	French – Atlantic Ocean	Spain – Atlantic Ocean	French – Indian Ocean	Spain – Indian Ocean
Length HT (m)	73.7 ± 1.15 (SV: 38.2 ± 3.2)	71.3 ± 1.2 (SV: 36.2 ± 2.6)	81.8 ± 0 (SV: 36.4 ± 4.5)	95.0 ± 1.6 (SV: 38.8 ± 5.3)
Decades of construction	1990-2000	1970-1980	1990-2000	1990-2000
Days at sea	251 ± 26	249 ± 29	261 ± 39	267 ± 24
Estimated fuel consumption (T)	1788 ± 314	2560 ± 236	2215 ± 246	4045 ± 472
Number of FAD buoys and rafts	249 ± 76	249 ± 76	688 ± 112	688 ± 112
Number of crew	PS: 28.3 ± 0.5 SV: 13.5 ± 1.7	PS: 27.1 ± 3.2 SV: 12.6 ± 2.0	PS: 32.3 ± 0.9 SV: 12.7 ± 1.2	PS: 36.5 ± 3 SV: 13.7 ± 0.8
Number of supply vessels	0.100 ± 0.007	0.3 ± 0.1	0.3 ± 0.1	0.9 ± 0.2
Life span of seines (y)	3	6	3	6
Dimensions of the seine	1600 m x 220 m	1600 m x 220 m	1800 m x 250 m	1800 m x 250 m
Landings of major tropical tunas (10^3 T)	4.54	5.89	5.7	10.58
FAD fishing rate (%)	49.8 ± 4.5	78.1 ± 6.8	75.3 ± 11.7	86.6 ± 7.2

4.2.4.2. Life cycle inventory (LCI)

Background data was chosen from the EcoInvent 3 © and Agribalyse 3 © database. Foreground data on the core and downstream since 2015 to 2019 was obtained from public data (i.e. catch data from ICCAT – www.iccat.int and IOTC – www.iotc.org), data from tuna observatories (Observatory of exploited pelagic ecosystems - Ob7, IRD and the Spanish Oceanographic Institute – IEO) and from compagnies meetings (see part. 3.4.1.). To process the life cycle assessment, we use the Simapro© software (developer version 9.4.0.2) (https://simapro.com/).

4.2.5. Life cycle impact assessment

The life cycle impact assessment was carried out using the method Environmental Footprint 6 (EF v. 1.03) (Fazio et al. 2018). The EF method provides fifteen impact categories. Six conventional impact categories are presented for reasons of clarity according to the type of impacts more frequently applied in fisheries seafood LCA studies (Abdou et al. 2018; Á. Avadí, Vázquez-Rowe, and Fréon 2014; A. Avadí and Fréon 2013; Hospido and Tyedmers 2005; Fernández-Ríos et al. 2022; Vázquez-Rowe, Moreira, and Feijoo 2012 ; Henriksson et al. 2012):

Global Warming Potential (GWP) – unit: kg CO2eq.: Global warming or climate change is a global problem resulting from the infrared radiative forcing effects of greenhouse gases. Global warming potential in life cycle assessment is measured in kg CO2-equivalent or carbon dioxide equivalents (IPCC 2013). Average temperature rises across the globe as a result of greenhouse gas emissions can be viewed as an exogenic pressure as, although emissions may be the result of local activities, the consequences from those emissions are at a global level.

Acidification Potential (AP) – unit: mol H+ eq.: Acidification is also a global problem resulting from the emissions of acid compounds from human activities. Acidification in life cycle assessment is measured using emissions in mol H+ equivalent (Posch et al. 2008). Acidification of our oceans leads to the reduction in the productivity of low trophic level organisms, such as plankton and shellfish. These reductions have a knock-on negative effect on fish stocks, which feed on these smaller organisms. Acidification can also be thought of as an exogenic pressure, as it is a global problem which will have impacts locally.

Ozone Depletion (OD) – unit: g CFC-11 eq.: Ozone depletion is a global problem resulting from the degradation of the ozone layer causing by human activities emissions of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). Ozone depletion can cause increased amounts of UV radiation to reach the Earth surface which can lead to an increase cases of skin cancer, cataracts and impaired immune systems. Excessive UV radiation can inhibit the growth of plants. Ozone depletion is measured using emissions in kg CFC-11 equivalent or trichlorofluoromethane equivalent (WMO 1999).

Eutrophication Potential in freshwater (EP, F) – unit: g of P eq. and in marine water (EP, W) – unit: g of N eq.: The emissions of phosphates and nitrates from activities on the land lead to run off of these nutrients into water bodies causing eutrophication, or the enrichment of water bodies with nutrients. The productivity of plant species, such as algae, in water bodies, is limited by the concentration of key nutrients, such as nitrogen or phosphorus. Eutrophication releases plant species from this limitation and results in algal blooms which can ultimately create dead zones for other species below the hyperproductive algae. Eutrophication in marine system is measured in kgs of N equivalent emissions, or nitrogen-equivalent emissions. Eutrophication in freshwater system is measured in kgs of P equivalent emissions and can be viewed as an endogenic pressure since these emissions have an effect on the local system.

Water depletion (WD) – unit: m^3 water depletion: The water depletion may be referred to product water footprint or water scarcity. The water depletion is measured in m^3 water eq. of deprived water (Available WAter REmaining - AWARE 100 based on UNEP 2016). The AWARE method is based on the inverse of the difference between water availability per area and demand per area. The water footprint of a product is the amount of water that is consumed or polluted in all processing stages of its production. A product water footprint quantifies how much pressure that product has put on freshwater resources. Notably the variables in the calculation of water footprint will vary depending on location, season but also on a yearly basis depending on the occurrence of extreme weather events such as drought

4.2.6. Life cycle impact assessment uncertainty or variability calculation

Several uncertainties or variability sources can appear on ICV data:

. the uncertainty on characterisation factor provided by the calculation impact method – this uncertainty can be assessed by testing different impact calculation method (Ecological Footprint, ReCiPe, etc.) – As fisheries impact is known strongly driven by fuel use consumption of fishing vessels, we assume the GWP will be the principal impact identified. Generally, the same IPPC method is used to calculate GWP impact in the different impact assessment methods (Simapro user guide). We assume that this source of uncertainty is negligible in the case of fleet impact assessments;

. the uncertainty inventory data from EcoInvent© database – Each processus from the EcoInvent data base have been modelized with an uncertainty (i.e. geography, time, process adequation) (Sup. Mat. 3.5);

. the uncertainty on inventory data created by the authors – the quality of the ICV data was provide thanks to distribution of data, and the matrix Pedigree score (Sup. Mat. 3.5);

. the variability due to the interannual flows data (average fleet activities on 2015 to 2019) – this variability on the ICV flow data has been tested by add the standard deviation on data when it was available and the data distribution associated (i.e. normal, lognormal). For the rest of ICV flow data we quantify the uncertainty using the pedigree matrix procedure (i.e. only a mean value available, without information about the uncertainty) (Ciroth et al. 2016).

A Monte Carlo simulation with 1,000 runs is carried out to determine how the intrinsic quality of the data used in the modelling may affect the outcomes.

4.2.7. Secondary data for different functional unit

Tropical tuna fisheries provide other services than kg of landed tuna, as social services (i.e. protein provider, employment, salary) or economic benefits (i.e. value of catch). In the literature, environmental burdens of industrial fishing fleets as tropical tuna purse seiners is largely driven by the fuel consumption (impact on CC – kg CO2 eq.) and they have an increased efficiency of the fuel-related inputs (Vázquez-Rowe et al. 2011). We propose to evaluate eco-efficiency of tropical tuna fishing fleets based on kg CO2 eq. in regard to other services providing by the fisheries. After assess the potential climate change impact of life cycle of fishing fleets, we convert the total kg CO2 eq./kg of landed tropical tuna into:

- kg of mature tropical tuna.kg CO2 eq.-1: We know the total catch landed, the species ratio (YFT, BET and SKJ) and the size specific data from Atlantic and Indian RFMOs for each fleet. We use the fished juvenile rate from Ougier et al. (Submitted) to calculate the fished mature rate (1-fished juvenile rate). The length at which half of the fish are mature (L50) are 110 cm for of YFT in Atlantic Ocean, 100 cm for YFT in Indian Ocean, 100 cm for the BET and 42 cm for the SKJ. The L mature 50 was defined based on the most recent stock assessment published (2019 for ICCAT, 2021 for IOTC) ;

- number of full time equivalent in FTE.kg CO2 eq.-1: the number of FTE of European purse seiner fleets is collected by the Scientific, Technical and Economic Committee for Fisheries (STECF 22-06 - EU Fleet Economic and Transversal data at fleet segment) of the European Union (EU). As the amount of FTE of each European purse seine fleets is aggregated for all ocean (Atlantic and Indian for French fleets and Atlantic, Indian and Pacific oceans for Spanish fleets), we proceed to an allocation step of each ocean by the landings in weight, as proposed by Ougier et al. (Submitted) ;

- net profit in €.kg CO2 eq.-1: The net profit of EU-PS fleets is calculated using data collected by the STECF as previously explain and proposed by Ougier et al. (In prep) (cf. 2.).

4.2.8. Impact assessment analysis

The impact assessment results are provided by Simapro© software (developer version 9.4.0.2) using the EF method. The impact assessment results correspond to the sum of impact for each impact category and each primary process modelled in Simapro. We run the impact assessment for each fleet and each year.

Impact assessment results for the four European tropical tuna fishing fleets are averaged to be compared with other protein resources (seafood, meat and plants). The aim is to understand which impact categories are of concern for tuna fisheries. Data for the comparison are coming from Agribalyse database© which can be downloaded in CSV format from there website (AGRIBALYSE 2023 - doc.agribalyse.fr). We use data on the environmental impact of raw conventional (non-organic) agricultural products leaving the farm (by kilogram). Agribalyse database© provide environmental impacts of the Environmental Footprint method. From the Agribalyse data©, we attribute to the “Meat” product family the following group of products: Cattle, Sheep, Goat, Pig, Poultry and “other animal production”. Fish and Seafood products categories are allowing to the Seafood family of products except for tuna product which have their own comparison category. We select and attribute to the “Plant” product family only plants that provide proteins which are “Nuts”, “Oil seeds” and “Cereals”.

For the impact categories selected, impact assessment results are aggregated by categories of fishing activities: Use of the boat, fishing gear (purse seine), salt, other waste, fishermen transport, FAD raft, average boat construction and fuel consumption, as it is a main hotspot in fishing activities and contributor to CC potential impact (Parker et al. 2018). The aim is to understand which fishing activity parts are main source of impact.

Impact assessment results are presented for each fleet and each fishing strategy (FSC/FAD). The aim is to understand which fleet does better and whether FAD or FSC tuna have a similar impact regardless of the fleet fishing them.

Finally, we present the carbon-efficiency results for each fleet and fishing strategies to understand whether these variables are interesting regarding other services rendered that are not directly assessed in the LCA. The carbon efficiency is assessed through three indicators: the economic efficiency (net profit in € / climate change potential in kg CO2eq.); the efficiency on tuna stock (mature tuna catch in tons/climate change potential in kg CO2eq.) and the social efficiency (number of full time equivalent/climate change potential in kg CO2eq.).

4.3. RESULTS

4.3.1. Environmental performance of tropical purse seiners fisheries – critical categories

Majority impact categories class food categories with a less impact for plants, the mean impact for seafood and the higher impact for meat production (acidification, climate change, marine and terrestrial eutrophication, ionizing radiation, particulate matter, ecotoxicity on freshwater, toxicity on human, resource metal and fossil energy) (Fig. 4.3). The eutrophication on freshwater provide the lower impact for seafood and the photochemical ozone formation and ozone depletion provide the higher impact for seafood. The water use and the land use is close for each production category but the meat category has the higher spread impact assessment on water and land use. The impact of tunas is close to the average impact of seafood products. Our results are close to the Tuna product category from Agribalyse database except for the water use (Fig. 4.3) but is still consistent with seafood products. The EU-PS tuna is concerned by potential impact on acidification (AP), climate change (GWP), ozone depletion (OD), marine and terrestrial eutrophication (EP,M & EP,T) water use (WD), particulate matter and resource use, fossil (RU,F), particularly for AP and OD, where tuna products are in the high range of impacts of seafood products (Fig.4.3).

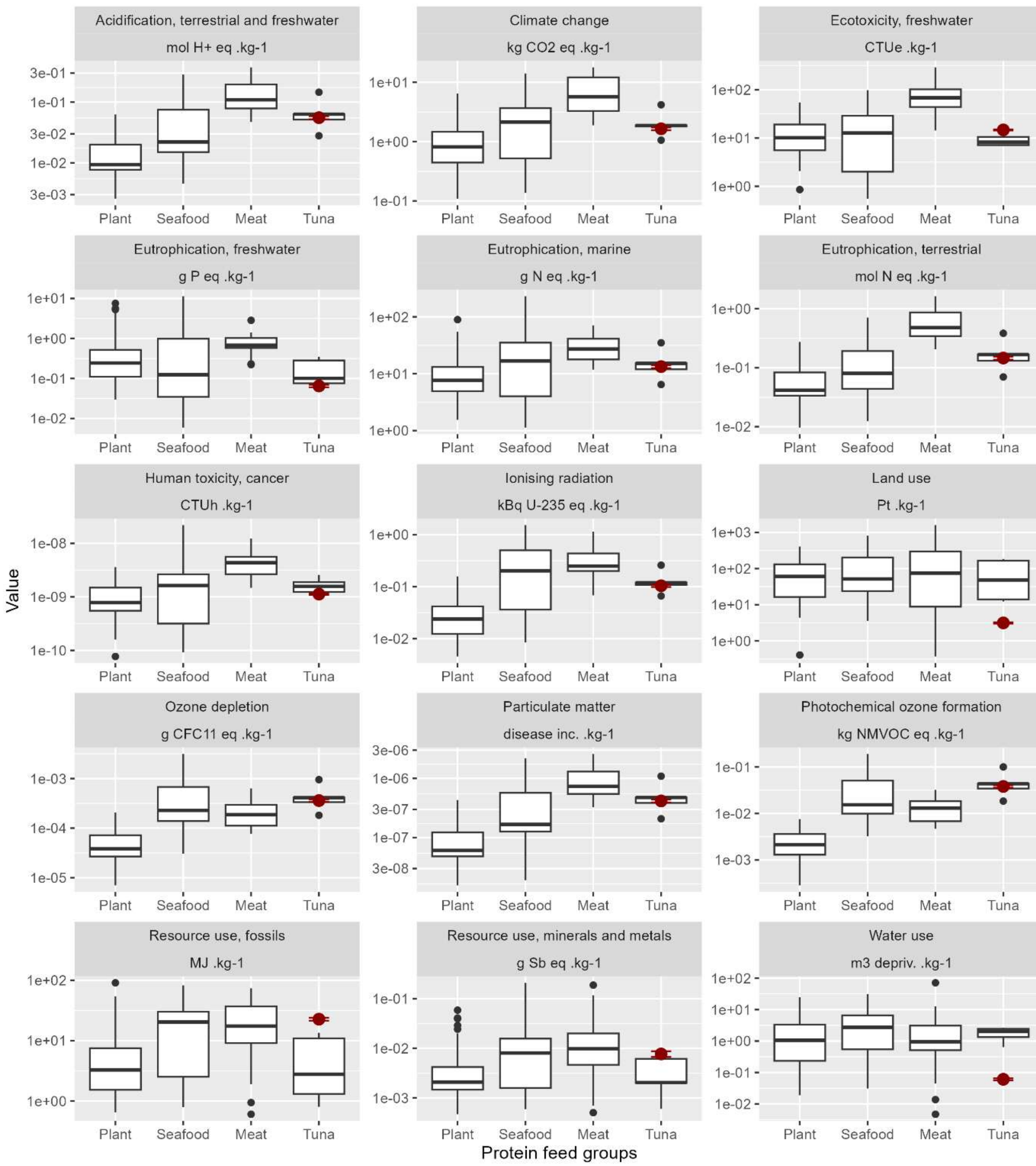

Figure 4.3: Comparison of impact assessment of the average European tropical tuna fisheries (red point and error bar around the average), with protein feed provider from Agribalyse database (2023).

4.3.2. Life cycle components participation to impacts

The diesel combustion of tropical tuna purse seiners is the primary source of all retained impacts categories (i.e. listed in Fig. 4.3) except for the water use, the minerals and metals resource and the eutrophication, freshwater (Fig. 4.4). The diesel combustion of purse seiner and supply vessels contributes to 85 ± 10% and 10 ± 10% to the climate change potential. The construction of boats (PS and SV) is the primary source of eutrophication (freshwater) and resource use (minerals and metals), respectively 70 ± 10% and 35 ± 10%.

The water depletion of tropical tuna purse seine fisheries activities is caused by the fishing gear (seine), which accounts for 40 ± 14%, the salt consumption for the brine, which accounts for 25 ± 6%, the boat construction, which accounts for 17 ± 4.5%, and the FAD raft, which accounts for 10% ± 8%. The use and maintenance of the boats and the fishermen's transport by plane have a negligible impact.

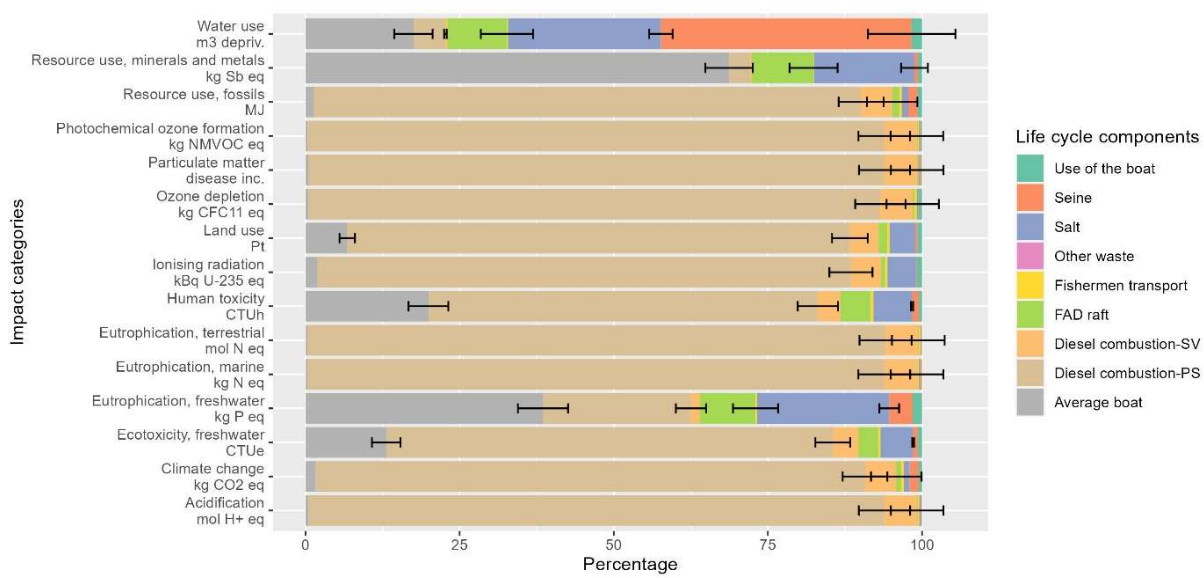

Figure 4.4: Average participation of life cycle components of the four European tropical tuna fleets producing 1 kg of tropical tuna (2015-2019) – yellowfin bigeye or skipjack tuna- to major impacts categories in percentage. The error bars correspond to the standard error around the average. Error bar are represented if the component of the life cycle has a participation rate of impact category more than 5%.

4.3.3. Differential impact of purse seiners strategies

The FAD tropical tuna has a higher potential impact on climate change than FSC tropical tuna (Fig. 4.5-A). The tropical tuna of Spanish fleet in the Atlantic Ocean have the higher potential impact on climate change for both fishing strategy than tropical tuna fish by other fleets (Fig. 4.5-B). The FSC tuna of Spanish fleet in Indian ocean have the less potential impact on climate change.

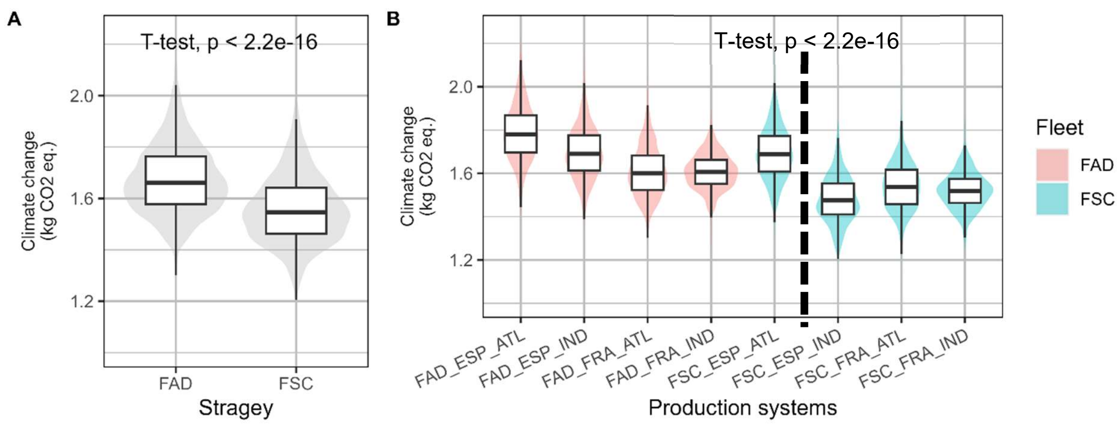

Figure 4.5: Potential impact of European tropical tuna purse seiner strategies (A) and fleets-strategies (B) on the climate change potential. In color (A) and grey (B), the distribution of statistical individuals calculated from the monte-carlo simulation.

Fleets of the Indian Ocean have a higher efficiency on tuna stock than fleets of the Atlantic Ocean (200-300 kg against 350-650 kg of mature tuna. T-1 CO2eq.) in the studied period (i.e. 2015 to 2019) (Fig. 4.6-A). The efficiency of tuna stock is stable in the Atlantic Ocean and increased in the Indian Ocean, reaching a pic in 2018. The French fleet in the Indian Ocean has a higher maximisation of their GWP impact on the tuna stock but a lower maximization of their net profit (Fig. 4.6-A & B). The economic efficiency trend of fleets is common, with a peak of around €380 T^{-1} CO2eq. reached in 2017, except for the French fleet in the Indian Ocean, with a peak of around €200 T^{-1} CO2eq. reached in 2018 (Fig. 4.6-A). The social and economic efficiency are the most variable between years. The social efficiency of French fleets is more variable than for Spanish fleets (Fig. 4.6-C). The French fleet in the Atlantic Ocean have the higher social efficiency in 2016 and 2017. The Spanish fleet in the Indian Ocean have a high maximization of mature tropical tuna (i.e. tuna length > L50, c.f. part 4.3.7.), net profit and a stable number of full time equivalent (FTE) provided, by GWP impact.

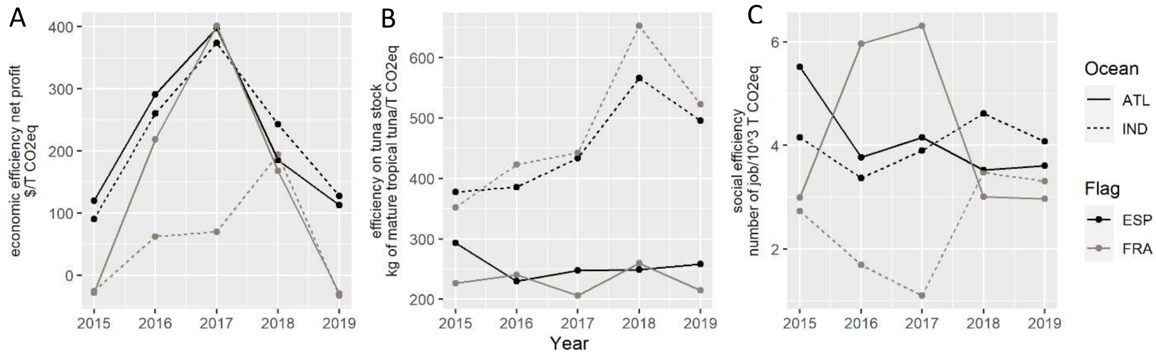

Figure 4.6: Position of the EU-PS fleets by years on three dimensions graph relatively to tree eco-efficiency dimensions i.e. economic efficiency (maximization of the net profit), efficiency on tuna stock (maximization of mature SKJ, BET and YFT tunas) and social efficiency (maximization of number of full time equivalent - FTE). The maximization is expressed relatively to impact on climate change (kg C02 eq.)

4.4. Discussion

In this study, we conducted a life cycle assessment of tropical tuna (SKJ, YFT and BET) caught by four European purse seiners (i.e. French and Spanish fleets in the Atlantic and Indian Oceans).

4.4.1. Environmental impact of EU-PS fleets and other food products

We compared tuna caught by EU-PS fleets with other protein human feed groups from Agribalyse database and found that acidification potential (AP), climate change potential (GWP), ozone depletion potential (OD), marine and terrestrial eutrophication potential (EP,M & EP,T) water use potential (WD), particulate matter potential and resource use potential, fossil (RU,F) are of concern for tuna fisheries, particularly for OD. We found the ozone depletion of tuna products is higher than meat category. For developing countries' fishing vessels, OD is generally caused by the ice-making machine on-board using CFC and HFC refrigerant gases (Wibawa et al., 2022). In our results, the OD is caused by maritime fuel combustion (95%). CFCs and HCFCs are forbidden since 1990's (Montreal Protocol, 1987[14]). HCFs are also listed as greenhouse gases by the Kyoto Protocol because of their relatively high global warming potential. In line with the Kigali (Rwanda) amendment signed in 2016, the EU Regulation calls for a phase-down of HFC consumption in 2030 to become only 21% to reduce

[14] The Montreal Protocol on Substances that Deplete the Ozone Layer, which entered into force January 1, 1989, appears at 26 I.L.M. 1541, 1550 (1987).

the impact on GWP ((Wibawa et al., 2022). In the literature, the maritime fuel combustion contribution to OD is not a highlighted concern (Roux et al. 2024). However, considering that tropical tuna product have a higher impact than other food products including meat (Fig. 4.3), we recommend this fishery industry to investigate the how their maritime fuel deplete the ozone layer.

The four fleets have a similar environmental impact pattern. Except for WD, these impact categories highlight the fuel consumption of vessels as a major contributor. The use and maintenance of the boats and the fishermen transport by plane have a negligible impact on the life cycle of tropical tuna catch.

The water depletion impact of EU-PS tuna is smaller than expected (factor 10) comparing to Agribalyse database and literature (Sup. Mat. 3.5). We suppose a water use reduction due to a change in net life span, as propose by Le Drezen (c.f. part 3.4.1.), as we used the same seine processus available in Agribalyse database (Cloâtre 2018). However, our result is consistent with the WD of seafood products of which water depletion remains a concern. Nexus water-energy-food is often studied to reduce the environmental impact of seafood products (Liu et al. 2020; Murali et al. 2021; Ruiz-Salmón et al. 2021). The fishing gear (nylon in the seine net) is the higher part of the WD impact (40 ± 14%). Nylon needs a high quantity of water in production, and this water needs strongly depends on the nylon market. The salt consumption contributes to water depletion of EU-PS fisheries (25 ± 6%). However, the salt impact on water depletion should be considered with caution as the salt used in the life cycle model is a mix of salt produced by evaporation and mine salt (50/50). In particular, the salt from mines causes a higher water depletion than evaporation water (Althaus 2007). The water depletion caused by the salt consumption has been allocated to each strategy effort based on the strategy catch of targeted tunas. However, DeBeer et al. (2019) showed that salt is absorbed by tunas (~50kg/T), and this absorption depends on the tuna size. The lower the size, the more absorption because of the higher ratio of surface/volume for smaller individuals. This higher salt absorption of yellowfin and bigeye juveniles and skipjack is well known by fishermen responsible for the salt concentration of the brine (Com. Pers. purse seine refrigeration officer). Thus, we can assume a higher water depletion for the FAD strategy than highlighted in this study.

To a lesser extent than salt and nylon, the use of metallic materials (the steel hull of the ship - 17 ± 4.5% - and the metal structure of the FAD – 10 ± 10%) also require water. The standard deviance around the water depletion cause by the FAD can be higher if we consider that Spanish fleets used more boys than assumed in our method during first years of the present study (Com. Pers. L. Dagorn, IRD). It should be noted that the environmental impact of the metallic FAD structure could significantly change if we consider a bamboo FAD structure, also used during the study period (Com. Pers. L. Dagorn, IRD). For a bamboo structure we assume a lower water depletion but a higher land use.

To reduce water footprint of tropical tuna, purse seiners fisheries should focus nylon and salt origin. Territorial LCA (T-LCA) is an emergent LCA approach assessing geographically defined systems which can focuses on the assessment of a specific activity or supply chain anchored in a given territory (Loiseau et al. 2018). Tuna fisheries are distant fisheries using materials and resources from different regions of the world with different waste and water treatments, territorial LCA could be relevant to better understand the water footprint of tropical tuna fisheries and more widely industrial fisheries. To our knowledge any T-LCA studies have been conduct on fisheries system.

In addition to the water footprint, derelict fishing gear (DFG) is one of the most abundant and harmful types of marine litter that gets increasingly retrieved from the ocean (Schneider et al. 2023). Tropical tuna purse seine do not reject their seine in the ocean but are concerned by derelict FAD (Basurko et al. 2022; Murua et al. 2023). For date plastic pollution from FAD, and more widly from fishing gears, is not weel assess in LCA as characterisation factors of plastic toxicity is marine water are limited (Moreno et al. 2023; Murua et al. 2023). Biodegradable FAD and recycle fishing gears have been explored to reduce fishing waste of tropical tuna purse seiners. Recyclage or waste treatment steps should also be approach with T-LCA as each countries and world region can have different territorial impact for a same service (Loiseau et al. 2018). However, mitigating the number of FAD beaching remains necessary for example with at-sea dFAD recovery that offers promising options for reducing the ecological footprints of purse-seine fisheries (Imzilen et al. 2022).

4.4.2. Carbon footprint and fishing strategies

Diesel combustion of fishing vessels is the major contributor of LCA impacts (method EF), i.e. more than 85%. This result is consistent with the literature which consider diesel combustion (or fuel use intensity) has the major impact for purse seiners (Hospido and Tyedmers 2005) and widely fishery activities (A. Avadí and Fréon 2013; Ramos et al. 2011; Vázquez-Rowe et al. 2011; González-García et al. 2015). Our results shown that the reduction of fuel use intensity (FUI) could have a significant effect on GWP and associated impact categories of EU-PS tropical tunas. We demonstrate that EU-PS tropical tuna catches on FAD has a higher GWP impact than FSC tropical tuna catches (FAD: 1.68 ± 0.14 ; FSC: 1.56 ± 0.13 in kgCO2eq./kg of tuna).

Concerning uncertainty around these results, Montecarlo simulation explore parameters uncertainty but parameters are considered independently from each other (i.e. without consider existing correlations) (Heijungs and Huijbregts 2004). We can assume that the uncertainty of our outputs is overestimated, as the sampling space created is larger than if correlations had been considered (Björklund 2002). However, our results show that only Indian Ocean Spanish FSC tuna has a carbon footprint similar to FAD tuna. (i.e. FAD from four fleets and FSC from SPA-IND together: 1.68 ± 0.13 in kgCO2eq./kg of tuna ; FSC from SPA-ATL, FRA-IND, FRA-ATL fleets together: 1.51 ± 0.11 in kgCO2eq./kg of tuna). The carbon footprint for these three FSC systems is reduced by 10.1% compared with the others (FAD systems and Spanish FSC in Atlantic Ocean). Is this difference coming firstly from a better fuel efficiency by vessel? A higher tuna catches by vessel? A Morris or Sobol' sensitivity analysis would identify the key/sensitive parameters leading to differences by strategy, fleet or even year (Garcia et al. 2019; Sobol' 2001).

Concerning GWP impact of FAD and FSC strategies, previous studies described FADs as fuel-saving tools to increase catch rates and reduce searching time (Dagorn et al. 2013; Scott and Lopez 2014; Basurko et al. 2023). In recent years, studies have suggested the opposite effect of FADs as they induce constant distances travelled from one FAD to another, for ultimately lower catches than on FSC (Chassot et al. 2021; Basurko et al. 2022)However, purse seiners use both FAD and FSC strategies simultaneously, making it difficult to allocate fuel consumption to one strategy or another. Basurko et al. (2022) compared fuel use intensity between strategy-driven trips, i.e. they compared fuel use intensity of oriented FAD strategy trips and oriented FSC strategy trips. In this study, total supply activities are considered as impact of FAD tuna because supply vessels are used by fishing vessels to assist them in FAD launching and maintenance (Arrizabalaga and De Molina 2001). Even if Basurko et al. (2022) found a higher fuel use intensity for the FAD strategy trips, they highlighted that this difference may be driven by seasonality and FSC availability, the number of FADs in an area, vessel characteristics and equipment, and skipper skills rather than the adopted fishing strategy. Indeed, FSC fishing needs searching time in the beginning, and then, fishing vessels can stay on FSC area for several days (Basurko et al. 2022). Our results provide a supplementary point of view showing that FAD strategy have a higher GWP impact than FSC strategies in average, considering inter-annual and inter-fishing practices variability.

The Spanish fleet in the Atlantic Ocean has the higher GWP impact compared to the other fleets for both strategies. This fleet is the only one to have an older fleet, with construction done in 1970-1980, which could induce a lesser fuel efficiency compared to more recent vessels (Chassot et al. 2021).

We found that the diesel combustion of supply vessels contributes to around 10% of each impact category (except for WD, EP,F and RU). The reduction on supply vessels could have a significant effect on majority impact categories of EU-PS tropical tunas assuming no effort report on FAD research, maintenance or other vessel equipment (satellite buoys, echo-sounders) by purse seiners. IOTC have decided to reduce supply vessels (SV) to two SV for five PS for 2020 (IOTC 2019) then three SV for ten PS for 2022 (IOTC 2021). On the 2015-2019 period, only the Spanish fleet in the Indian Ocean do not respect this resolution (Table 2: 9 SV for ten PS). The SV number reduction conduct to variations in DFAD fishing effort and can provide complex response of catchability on tuna stock (Tidd et al. 2023) and tuna market (Cheilari et al. 2013; Patrice Guillotreau et al. 2017).

Further research using consequential-LCA (CLCA) could describes the environmental consequences of an fisheries management action/decision by including market mechanisms into the analysis (Zamagni et al. 2012; Vázquez-Rowe and Benetto 2013; 2014). In reaction of tuna and gasoil price change, compagnies costs could change (Guillotreau et al. 2022) as perhaps supply decisions (i.e. salt or nylon origin) leading to change in environmental impact.

In the case of tropical tuna purse seiners, high heterogeneity of territories impacted, positively or negatively by EU-PS fisheries raise questions about territorial environmental consequences (i.e. increasing water depletion if nylon coming from Indian than Europe) which can by approach by territorial-LCA (Loiseau et al. 2018). FAD use has positive impact on territories as tuna-like and other species bycatch provider for local territories (i.e. Abidjan, Seychelles, Maurice) by "faux-poisson" market (Romagny et al. 2000). These market dynamics raise questions about the capacity of markets and territories to be adapted to fishing activity changes in terms of areas and quantities (e.g. FAD fishing or quota reductions) (Guillotreau et al. 2023). Sensibility analysis is an interesting step to simplified parametrized LCA model to evaluate scenario for management in attributional LCA (Padey et al. 2013). In a context of energy transition, waste management of derelict fishing gear (Schneider et al. 2023), simplifying LCA could make possible multiple scenarios tests at lower costs, for example, for forecasting purposes (Ventura 2022).

4.4.3. Carbon-efficiency of EU-PS fleets

In literature, eco-efficiency in fisheries shown that important reductions in environmental impacts could be attained if most vessels were to operate at higher levels of efficiency (González-García et al. 2015). In their review on the concept of eco-efficiency in fisheries, Piwonska (2021) argue that "further studies on eco-efficiency in industrial fisheries needs to include social factors and perhaps those related to biodiversity". In this present work, LCA assessment is studied relatively to purse seiners carbon-efficiency on tuna stock (i.e. capability to catch mature tuna and limit impact on spawning tuna biomass, for one kg of CO2eq. emitted), on number of full time equivalent (FTE) and on net profit of fleets.

The carbon efficiency of fleets on tuna stocks is characterized by ocean variability, i.e., higher efficiency in the Indian Ocean than in the Atlantic Ocean. This difference in carbon efficiency by ocean is relative to yellowfin and bigeye tuna catch and, more recently, skipjack catch since 2018 (Sup. Mat 3.7), which can be explained by different states and management of tuna stock by tuna RFMOs (Atlantic Ocean: ICCAT - www.iccat.int, Indian Ocean: IOTC - iotc.org). The carbon efficiency of fleets on BET and SKJ tunas in the Indian Ocean increase, particularly after 2017, while the carbon efficiency of the Spanish fleet on YFT decrease on the all period. In the Indian Ocean, total allowable catch (TAC) of YFT has been settled since 2017 (IOTC 2016). For

Tolotti et al. (2022), the fishing companies manage the quota throughout the year by using more FADs (catching few YFT but more SKJ in terms of weight) than before the quota system was set up. Major SKJ catch on FAD is mature, which is consistent with an increase of SKJ mature catch of EU-PS fleets in the Indian Ocean. An increase in carbon efficiency relative to mature bigeye tuna in the Indian Ocean in 2018 remains surprising, particularly for the Spanish fleet, for which eco-efficiency doubled in 2018 and then returned to a level similar to 2017 (Fig. 4.6-B).

Among the four industrial tropical tuna purse seiner fleets operating between 2015 and 2019, the most eco-efficient fleet is the Spanish fleet in Indian Ocean which maximizes its GWP impact in economic terms (net profit) and on stocks (tonnage of mature tuna), and have a stable social efficiency than other fleets. This result raises questions as the Spanish fleet fishes the most under FADs and therefore has the greatest impact on ecosystems comparing to FSC fishing i.e., high rate of by-catch, high rate of juvenile YFT and BET tuna) (Murua et al. 2021). Even though FAD fishing is tending to become more fuel-intensive than before (Basurko et al. 2022), FAD fishing allows an increase in catch stability and yield per recruit (Dagorn et al. 2013). Ougier et al. 2024 show that Spanish fleets have a higher net profit than French fleets and that this economic performance is correlated with the use of FADs (analysis carried out from 2009 to 2019). EU-PS economic performance is linked to rise of tuna price in accordance to gasoil price (Guillotreau et al. 2022).

A negative net profit was found for French fleets in 2015 and 2019, meaning these fleets had higher costs than turnover. However, this result should be interpreted with caution. The fleets' turnover and expenses come from STECF data (version 2022-06), which are fleet declarations. Revenue is coming from landings sales. No other revenue sources have been declared (e.g., operating subsidies, income from leasing out quota, other income). Economic data are provided at the fleet segment scale, which differs from the company scale. A fishing company can have vessels with different flags, e.g., French, Seychelles, Mauritius, etc., and different fishing activities, such as purse seine tropical tunas fishing and longline toothfish fishing. Thus, these data inform on net profit made by French-flagged purse seiners but do not directly assess net profit realized by French fish companies. A negative result is probably found for both fleets of the same flag because the economic data of distant European fleets is declared at the global ocean scale by the STECF, then allocated to each ocean by the fishing effort (kW) (Ougier et al. In prep).

4.4.4. Perspectives for carbon-efficiency for fisheries

In this study, we propose a method to compared LCA assessment impacts and eco-efficiency between four European purse seiners fisheries using only collecting data. The use of collecting data allows researchers to gain a number of advantages. With the development of a code routine, it would be possible to simultaneously obtain calculations of eco-efficiencies or inefficiencies of fisheries, i.e. without a questionnaire step for ILCA. The Brigthway package could offer this perspective and respond to research demand on more consideration of socio-economic issues for fisheries (Piwońska 2021; Á. Avadí, Vázquez-Rowe, and Fréon 2014; Laso et al. 2018; A. Avadí and Fréon 2013). Here we discuss three carbon-efficiency components relative to tuna spawning biomass catch (ecology), net profit (economy) and FTE (social) allowed by similar industrial tuna fisheries, but in their dashboard of ecologic and socio-economic indicators, Ougier et al. In prep propose a dashboard of ecological, technical and socio-economic indicators for industrial and artisanal tropical tuna fleets operating in the Atlantic and Indian Oceans since over several decades. If we assume the fuel consumption of vessels as the major fisheries impact, this work could help to compare eco-efficiency of a large different tropical tuna fisheries. *Do industrial fleets have a higher eco-efficency than artisanal fisheries ? According to what criteria ? Did this eco-efficiency change with time, i.e. seaons and years ?* Piwońska (2021) explains that eco-efficiency in fisheries could lead to define industrial fleets as the most eco-efficient fleets compare to others fleets segments because industrial fisheries are already optimized their consumption of resources use (Vázquez-Rowe et al. 2010; 2011; González-García et al. 2015). However, further eco-efficiency in fisheries research comparison need to integrate social and biodiversity parameters rather than referring to economic eco-efficiency (Ryberg et al. 2020).

4.5. Conclusion and recommandations

We used annually collected data from four tropical tuna purse seiners (EU-PS) that targeted Skipjack, Yellowfin and Bigeye tuna, in Atlantic and Indian Oceans, to evaluate the environmental impact and eco-efficiency of these important tuna fisheries. We compare environmental impact of EU-PS tuna with other food production from a public database

(Agribalyse©). Overall, the major impact categories that fisheries research needs to consider are the impact on climate change, the water footprint, in line with the energy-water-nexus theory and the ozone layer depletion. The fuel consumption is the first contributor to potential climate change potential and the ozone layer depletion (around 90%). The supply vessels of these fisheries contribute to around 10% of these impacts. A reduction of supply vessel could improve environmental performance of EU-PS fleets but further research is needed to assess potential impact of a report of fishing effort. Vessel technologies and fishers behavior changes over time and between FAD and FSC should be further explored to better characterize report of effort, e.g. of a seasonal FAD moratorium. Report of effort would change impact allocation to each strategies and thus, change tropical tuna purse seine fisheries life cycle assessment results, in terms of fuel efficiency, gear use, salt consumption. The fishing gear and the salt consumption for the brine (i.e. nylon and salt origin) are the major contributor to the water footprint of EU-PS tropical tunas (35% and 25% respectively). Fisheries companies could examine the water footprint of the different origins of salt and the nylon that makes up salt. The impact of the crew transport by airplane is negligible but the FAD raft construction provides a supplementary water footprint for FAD tuna (around 10%). Further research in LCA methodology is necessary to better quantify impact of the end of life of FAD raft on marine environment as plastic pollution, which is still poorly understood and recorded in databases of inventories.

We have demonstrated that tuna fished on Free School (FSC) has a smaller carbon footprint than tuna fished on FAD for all EU-PS fleets except for the Spanish fleet in Atlantic Ocean. This fleet differs from the other by an older vessel fleet modelized (engine construction 1970-1980). This fleet have similar carbon footprint of FSC tuna than FAD tuna. However, it maximizes its global carbon footprint in terms of services provided to tuna stocks (mature tuna fishing), to the business economy (net profit) and more recently, to number of full time equivalent (2018-2019). It would be interesting to compare these results with other types of fishery (other gears or small-scale fisheries). Based on annually collected data, a life cycle assessment routine could provide an effective response to such comparisons and enable future improvements to inventory databases to be considered.

4.6. REFERENCES DU CHAPITRE 4

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5. GENERAL DISCUSSION

5.1. INTRODUCTION

The concept of sustainability has been defined through the 17 sustainable development goals (SDGs) (UNO, 2015). Fisheries aspire to ensure food security for humanity but represent the principal impactful activities for marine ecosystems (IPBES, 2019). Methods for assessing the sustainability of fisheries need to comprehensively consider both positive and negative aspects of fisheries activities and their value chain to enlighten stakeholders and facilitate decision-making effectively. This study employed two multicriteria approaches to assess and monitor the sustainability of data-rich fisheries. This work's originality lies in combining these two different approaches in a single case study. The main question was "**What synergies can be built up between multi-criteria assessment approaches, such as a dashboard and LCA, to appraise the environmental sustainability performance of fisheries in the triple dimensions of ecological, economic and social?"**. To address this question, the case study selected was the European tropical tuna purse seine fishing fleets in the Atlantic and Indian Oceans, chosen for the extensive data availability. Public data have been utilised to the fullest extent possible. Open access methodologies and data have been proposed wherever possible to adhere to the FAIR principles (Wilkinson et al., 2016).

Chapter 2 aims to answer the first question: **"Given the current state of knowledge and existing data collection on tuna fleets, what criteria can be assessed and monitored in a dashboard of ecological, economic and social performance indicators?"**. Ecological data from Regional Fisheries Management Organizations (RFMOs)[15] provide a comprehensive overview of the ecological performance of tropical tuna fishing fleets well beyond the purse seine case study. However, economic and social data cannot substantially compare fishing gears and flag usage in the Atlantic and Indian Oceans. This lack poses a major challenge for RFMOs and stakeholders, necessitating the collection of high-quality data on small-scale fleets, i.e. on

[15] E.g., catch data by species, catch size data, fishing effort

ecological and socio-economic dimensions, to prevent these fleets from being overlooked in future research and management decisions.

This work raised major methodological challenges:

(1) Develop a dashboard using various public datasets from different sources (tuna RFMOs and the European Scientific Technical and Economic Committee for Fisheries, STECF), each adhering to other data collection rules.

(2) Socio-economic data for tropical tuna fisheries from RFMOs in the Atlantic and Indian Oceans are unavailable. While Annual Economic Report data, established for all EU fisheries by STECF, have been available since 2008, data from distant fisheries are aggregated by ocean and fleet segment, i.e., under the "Other Fishing Region" categories. To address this limitation, an adaptable disaggregation methodology has been implemented to increase the resolution of the socio-economic data for different fleet segments.

In Chapter 3, the generated dashboard was applied to investigate tropical tuna fishing fleets' ecological and socio-economic performances yearly over multiple years, i.e. 1960-2019 for ecological indicators, 2009-2019 for socio-economic indicators, in the Atlantic and Indian Oceans. The objective of Chapter 3 was to address the second question: **"What does a dashboard of indicators reveal about the sustainability of tuna fleets? To what extent do these fleets demonstrate sustainability concerning these criteria?"**. According to the selected criteria, we found that tropical tuna purse seiner and baitboat fisheries have higher ecological performances than longliners and gillnetters regarding species-based selectivity. Ecological performances of tropical tuna fisheries on marine ecosystem must be discussed in the light of the species-based selectivity and the trophic level of the bycatch. The post-release mortality by species for the different fishing *métiers* should also be assessed, but further research is needed. The economic performance of tropical tuna purse seiners seems to conflict with their ecological and social performances. Data lack poses a challenge for RFMOs, necessitating the collection of higher quality data on bycatch, i.e. increasing human or electronic observer coverage, and more widely, the collection of economic and social data on their fishing fleets to initiate a holistic performance monitoring of fishing fleets and *métiers*.

In Chapter 4, a life cycle assessment (LCA) was conducted on landings of tropical tunas by French and Spanish purse seiner fleets, considering their fishing strategies (FAD or FSC) at a year resolution (2015-2019). The objective of this chapter was to address the third question: "**To what extent does the LCA approach provide information on the diverse impacts of European tropical tuna seine fleets and their fishing strategies?**". We found that the environmental impact of tropical tuna purse seine fisheries was associated with water and energy use, in line with the energy-water nexus theory, and the ozone layer depletion. Fuel consumption is the first contributor to energy use and ozone layer depletion. Accounting for supply fuel consumption and FAD raft construction, we identified that the FAD métier exhibited a higher climate change potential than the FSC métier. The fishing gear and the salt consumption for the brine are the major contributors to the water footprint of EU-PS tropical tunas (35% and 25%, respectively); however, this contribution is dependent on their production origin (i.e. nylon and salt origin). This research required substantial data on annual fishing activities and consumption, which are unavailable (e.g., the number of FAD rafts, structures, number of fishing and supply vessels in activities, age of vessels, salt and nylon origin, etc.). Collaboration with observatory and tuna companies was essential to gather this data. To model fuel consumption, we opted to employ the model developed by Chassot et al. (2021) to mitigate potential biases arising from declared Annual Economic Report (AER) data. In this last chapter, we compared the disparities between our methodology and the utilisation of the Chassot et al. (2021) model.

A significant challenge of this study lies in bridging distinct fields of expertise:

1. Expertise in tropical tuna fisheries science, essential for adeptly handling and filtering the data related to fleets of interest.
2. Technical expertise on data to assess sustainability at fishing fleet resolution, e.g. various data sources, socio-economic aggregated data
3. Strong technical skills are necessary to understand and construct the Life Cycle Assessment (LCA) and the dashboard using annual data.

The following points illustrate this challenge.

Chapters 3 and 4 help answer the fourth research question: "**What are the main factors influencing the sustainability of tropical tuna fishing fleets? Can we identify strategies to enhance their management?**". In the subsequent paragraphs, some overarching considerations are highlighted regarding (1) the advances for fisheries management, (2) the limitations of the study, (3) the methodological issues addressed in this study, and (4) the current challenges for the sustainability of tropical tuna purse seiners. Additionally, the chapter develops potential future applications and enhancements for the proposed framework.

5.2. ADVANCES FOR FISHERIES MANAGEMENT AND RECOMMENDATIONS

5.2.1. Recommendations for fishing companies to reduce their environmental footprint with an LCA perspective

In Chapter 4, we argued the importance of the climate change potential and the water depletion impact category for tropical tuna fisheries activities (energy-water nexus). Carbon emissions could be further reduced by the development of more efficient motors (e.g., electrical engines) and route-planning tools (Granado et al., 2021; Pons et al., 2023). The LCA approach could inform on ecological consequences for other impact categories (e.g., metal resource depletion of electrical engines).

We demonstrated that FAD raft construction and their number contribute to water depletion (~10 % of the total water depletion). Resource use (minerals and metals) and eutrophication are influenced by vessel construction (metal), salt consumption for brine, FAD construction (raft) and gear production (nylon). Practical changes to reduce the impact of these components should be studied as a priority by fishing companies.

The high proportion of salt consumption contribution to water and mineral resource use (~20%) is interesting because this was not expected by the stakeholders (Comm. Pers. CFTO, ORTHONGEL). This significant impact of the salt could be a consequence of modelling choices. In the absence of information on salt origin from the tuna companies during the study, we used similar salt EcoInvent processes as Aubin et al. (2018) i.e. from mining salt, requiring large quantities of water and energy, rather than evaporating salt (Althaus, 2007). A change in data choice may reduce water depletion to ~15%. Supplementary data on salt production origin are necessary before any conclusion.

5.2.2. Advance and challenges for environmental assessment of fisheries

In the LCA approach, fuel consumption does not highly contribute to all environmental impacts. It is important to understand the potential environmental consequences of changes in fuel consumption level, e.g. due to associated technologies and fishing methods changes, to avoid impact transfer. For example, changes in fishing strategies, behaviour or construction of new fuel-efficient or electric vessels could have environmental impact transfer, e.g., water depletion, and mineral resource depletion, which should be studied to inform decision-makers. Based on this work, water depletion, mineral resource depletion and the climate change potential can be relevant to completing the environmental dimension assessment of a holistic dashboard on fisheries activities. Recently, Pak et al. (2023) have conducted a correlation analysis between eight impact categories of life cycle assessment of 1548 food products from the French database AGRIBALYSE to explore if the climate change potential (CCP) could be a proxy of all impact categories. The study reveals that, on the one hand, the CCP could act as a proxy for some of the impact indicators in the product categories, but the CCP indicator could not serve as a stand-alone indicator to represent environmental sustainability.

In addition to LCA impact categories on water depletion, mineral resource depletion and climate change, other indicators of the sustainability of fisheries should be considered, such as plastic pollution. Eliminating plastic production and increasing recycling is a major challenge for human societies. Plastic pollution was not considered here while, of the 8,300 million tons (Mt) of plastic produced from 1950 to 2015, only 7% has been recycled, and more than half has been discarded in landfills or leaked into the environment (Boucher et al., 2019). The cumulated stock in aquatic environments reached 139 Mt in 2019 (OECD 2022). For example, tropical tuna purse seine fisheries contribute to plastic pollution through FAD debris (Moreno et al. 2023; Zudaire et al. 2023; Murua et al. 2023) and fishing gear accumulation, especially in small island developing states (Guillotreau et al., 2023a).

The end-of-life of fishing gear in developing states (Seychelles, Mauritius, Ivory Coast, Ghana (Tema) and Madagascar (Diego)) and FAD rafts are not well known (Chapter 4). Moreover, the existing methods of the LCA approach do not well consider chemical marine impact or plastic pollution (Loubet et al., 2021). There is currently no standard methodology to measure the extent of the plastic problem (Boucher et al., 2019). For the moment, LCA, Material Flow Analysis (MFA) and Environmentally-Extended Input-Output Analysis (EEIOA) represent useful approaches to estimate plastic flow but do not provide chemical impact on marine waters (Guillotreau et al., 2023a).

The consequences of plastic debris on marine biodiversity remain unknown at scales greater than individual organisms and not spatially distributed when using LCA methods (Woods et al., 2016). More ecotoxicology studies are needed to better assess plastic consequences in marine ecosystems, e.g. to construct new characterisation factors for LCA methods (Loubet et al., 2021; Wermeille et al., 2023). Meanwhile, research progress in plastic impact assessment, data collection on the quantities produced and their end-of-life should be encouraged to complete a dashboard of fisheries sustainability e.g., plastic use intensity indicator (Guillotreau et al., 2023a). In the seafood sector, plastic pollution is more studied at the packaging step, but data collection on quantities of plastic materials used at production steps, i.e. fisheries, is encouraged (Ziegler et al., 2018; Weißbach et al., 2022).

5.3. ISSUES AND LIMITATIONS OF THE STUDY AND RECOMMENDATIONS

5.3.1. Data coverage and quality

Data coverage and quality, available from RFMOs and STECF of the EU, depends on the proper collection and transmission of data by the Member States. This work employs data up to 2019. The following section discusses data quality and coverage issues over the study period as they may influence our results. Their recent updates and changes in management rules that may influence the results of this work are also discussed.

Socio-economic data employed in this study come from STECF (AER 21-08). This European database is a compilation of different data collection frameworks, i.e. Council Regulation (EC) No 199/2008 of 25 February 2008 for the years 2008-2016 (DCF) and Council Regulation (EC) No 2017/1004 of 17 May 2017, for the years 2017-2019 (EU-MAP). In the AER 21-08 and the new version AER 23-07, submissions from France and Spain remain incomplete, especially for the period 2008-2010, which impacts time-series analysis and indicators calculation. In our analyses, data from 2008 was not considered for this reason, although 2009 and 2012 years significantly impacted correlations between indicators (Chapter 3). The lack of data quality could be a supplementary driver for this result, in addition to the economic specificity of these years discussed in Chapter 3, i.e. piracy in the Indian Ocean and the high tuna price, respectively. Robustness analysis by random sampling of statistical individuals should be performed for future studies.

Moreover, several Member States, including French and Spanish, continue to provide 'zero' values for several of the new EU-MAP variables (debts, assets, investments in tangible assets, subsidies on investments, operating subsidies, etc.). The economic performance assessment of these fishing fleets is therefore limited, particularly in assessing net profit and RoFTA, which are key to economic performance assessment. In addition, such data may improve transparency and allow equality assessment with coastal and small-scale fisheries (Appadoo et al., 2022).

Social data from STECF (AER 21-08 and AER 23-07) propose employment, expressed using job numbers and full-time equivalents. The multiannual program for data collection (EU MAP) (Decisions (EU) 2021/1167 and 2021/1168) specifies new social variables to be collected every three years from 2018 onwards: Employment by gender; Full-Time Employment (FTE) by gender; Unpaid labour by gender; Employment by age; Employment by education level; Employment by nationality; Employment by employment status; Total FTE National. The collection of such variables by all RFMO's state members should be encouraged, as salary by social categories, to allow for quantifying social inequalities (Van Holt et al., 2016). As ecological assessment depends on observer data quality, observers on board should be considered in the social categories proposed (Garcia, 2024). However, such requests may not be successful due to their illegal nature, e.g. currently, the unpaid labour variable remains incomplete by state members in the new version (AER 23-07) because assumed to be "a minor issue" (Prellezo et al., 2023)The European Union and RFMOs must remain vigilant and restrictive in order to achieve SDGs 4, 5, 8, and 10.

Regarding economic performance, it must be noted that some Spanish and French operators are the beneficial owners of purse seine vessels flagged and registered in third countries such as Seychelles, which are coastal states of IOTC and have their own quotas. Although this fleet is not part of the analysis under the EU-MAP, this might imply in terms of calculation of cost structure and economic returns for some of those companies which act as holding due to integration of their economic activities as European investments in third countries with likely financial transfers to the parent company (Prellezo et al., 2023).

Concerning the ecological performance of tropical fisheries, currently, there is a non-existing level of reporting of by-catch data e.g., dolphin fish, wahoo, barracuda, shark species, sea turtle species, marine mammals species, by most cooperating non-contracting parties (CPCs). This ends up in a rough estimation of nominal bycatch and discards (Prellezo et al., 2023). These lacks are particularly important for coastal countries and small-scale fisheries, which must be considered before concluding on the ecological performance of different fleets, i.e. industrial and small-scale fleets, based on the dashboard of indicators proposed in Chapter 2. More widely, the lack of cooperation between CPC countries is a major challenge for RFMOs, particularly in the Indian Ocean, in order to improve data quality and cooperation in setting quotas, participating in the conservative effort and preserving the resource (Fujii et al., 2023).

For better scientific data collection, IOTC adopted in 2022 a proposal to set up minimum electronic monitoring standards (electronic monitoring system - EMS - or Remote Electronic Monitoring - REM). The IOTC is the first RFMO that has adopted such standards. This will allow for raising the observer coverage. This measure application for small-scale fisheries remains a technical challenge (Monin et al., 2017), but could improve bycatch and discard data quality (half of the catches in IOTC are taken by artisanal vessels - Appadoo et al. (2022)).

Finally, the IOTC also imposed a YFT quota and, more recently, a reduction in the ratio of 2 supply vessels (IOTC, 2019) for 5 purse seiners to 3 for each 10 (IOTC, 2021). These measures combined could have an effect of effort displacement towards EEZs of countries where the EU has tuna agreements in place (Seychelles, Ivory Coast, Gabon…) or fishing in international waters. The recent STECF report on European socio-economic data analysis (Prellezo et al.,

2023) supposed that fewer supply vessels could induce time changes in fishing trips, costs, and energy efficiency of purse seine fishing fleets.

5.3.2. Limits of fuel consumption data collection

In both dashboard and LCA approaches, fuel consumption is established as a key factor of the sustainability of tropical tuna purse seiner fisheries (Chapters 3 and 4). In Chapter 4, Chassot et al.'s (2021) model was applied to quantify fuel consumption data of purse seiners fleets using vessels and fishing activity characteristics (Equation 1). This model does not consider directly supply vessel consumption because of a lack of bunkering data. We estimated the supply vessel consumption as 15.3% ± 1.5 of a purse seiner on average in the Indian Ocean. We applied this percentage in our study on each purse seiner fuel consumption estimation in the Atlantic and Indian Oceans (Chapter 4). Given the significant contribution of supply vessels

Equation 1: Fuel consumption model of purse seiners in the Indian Ocean, adapted from Chassot et al. (2021). Where F: Fuel consumption (Litre), LOA: Length overall, C: Construction period, D: Number of days at sea, S: Number of fishing sets done on FSC or FAD. v and Y indicate vessel and year, respectively and the model residuals Ɛ v;Y were assumed to be independent and identically distributed normal variables with mean zero and constant variance. There were no significant differences between years of activity (red cross)

$$F_{v,Y} = s(LOA_v) + C_v + s(D_{v,Y}) + s\left(S_{FAD_{v,Y}}\right) + s\left(S_{FSC_{v,Y}}\right) + \boldsymbol{\times} + \varepsilon_{v,Y}$$

to the climate change potential of tropical tuna purse seiner fisheries (around 10%) and tuna caught on FADs, their fuel consumption needs to be better evaluated.

In Figure 5.1, we compare fuel use data from AER corrected by our disaggregation method (Chapter 2) to the application of the fuel consumption of purse seiner and supply vessels estimated with the model of Chassot et al. (2021). This last model considers supply vessel consumption, while this consideration in the AER has been assumed not to be the case because it was unclear at the beginning of the PhD. (STECF 2017 ; Guillotreau Comm. pers.) (Chapter 4). Over the period 2015-2019, a similar fuel consumption was found between both methods, especially for the Spanish fleet in the Atlantic Ocean. The AER data combined with our method gives higher fuel consumption to other fleets than the model of Chassot et al. (2021). On average, the disparity in fuel consumption between the two methods is around 20%. Two hypotheses are formulated: (1) the AER consider the fuel consumption of supply vessels, or/and (2) the disaggregation method overestimates fuel consumption for these fleets. The data in the AER for the "Other Fishing Region" category, corresponding to EU distant fisheries, would benefit from increased precision regarding supply vessel consideration and should be detailed by oceans.

In the LCA approach, the confidence interval on fuel consumption corresponds to interannual variability (2015-2019), i.e. a confidence interval below 20%. Uncertainty around results from the chapter 4 could be underestimated. Therefore, the difference in climate change potential between FAD and FSC strategies should be manipulated with precaution. A sensitivity analysis of parameters in the LCA approach, e.g. fuel consumption estimation parameters, could provide insights into the significance of the fuel consumption parameter for each LCA impact category, e.g. using Sobol or Morris indices (Sobol' 2001; Garcia et al., 2019). A similar sensibility analysis could be performed for AER data. Increasing data quality on fuel consumption of fishing vessels is a great challenge to assessing the fisheries' climate change potential impact (Chassot et al., 2021; Basurko et al., 2023).

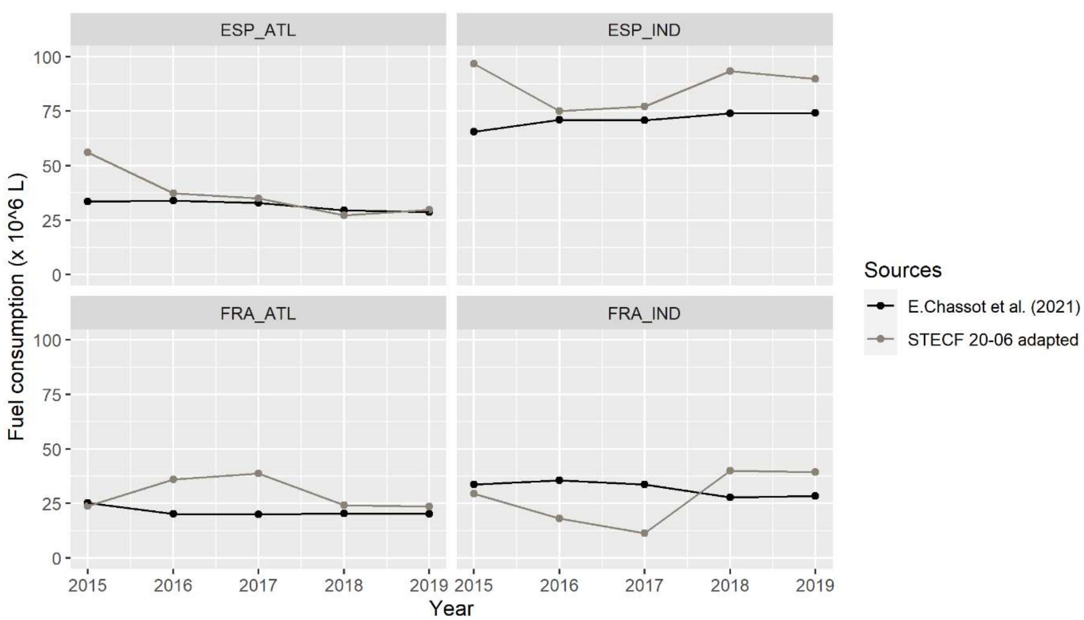

Figure 5.1: Comparison of absolute fuel consumption (L) data sources for the period 2015-2019 by fishing vessel.

5.3.3. Absence of climate change consideration in the sustainability assessment

An important limit of this work is the lack of climate change impact consideration on fisheries. Chapter 1 proposes indicators based on the ODD criteria (ONU) framework, i.e. what is desirable for the future. Fleet adaptation capacities, vulnerabilities or sensitivity to climate change is not assessed by the dashboard of indicators proposed. However, climate change consequences in the Anthropocene are a major challenge for sustainability assessment. Many researches have been carried out on climate change's impact on fisheries, e.g., considering biodiversity, ecosystem or socio-ecosystem consequences (Dueri et al. 2016; Marsac 2018; Barange et al. 2018; Dorji, Morrison-Saunders, and Blake 2023; Lam et al. 2020). Latitudinal shifts in tuna distribution may affect industrial and coastal fisheries (Barange et al. 2018). For the 2041–2060 period, Lam et al. (2020) estimate a change of maximum catch potential of -45% and -30% in the tropical zone of the Atlantic and Indian Oceans, respectively, under Representative Concentration Pathway 8.5 (RCP 8.5)[16]. Coastal fisheries, particularly small-scale fisheries in developing countries (SSFDC), are highly vulnerable to climate change because of critical habitat degradation (coral reef, mangroves, and saltmarshes), dependence on marine resources and limited adaptive capacity (Green et al. 2021; Dorji, Morrison-Saunders, and Blake 2023; Appadoo et al. 2022; Monnier et al. 2020; Lam 2020). Preserving food security for these coastal countries is a main challenge for responsible and sustainable fisheries (FAO 1995; SDG 2).

Chapter 2 demonstrates the lack of social and socio-economic data on tropical small-scale fisheries and calls on RFMO member states to proceed with these collections to avoid small-scale fleets' invisibility in the face of industrial fisheries (e.g. by collecting data on specific catch in weight and value, number fishermen and social wellbeing indicators (Van Holt et al. 2016)). More research and political positions are needed to ensure that (1) climate change and (2) industrial fisheries will not compromise the existence and adaptability of these SSFDCs.

For the first point, we need standardised measures of the vulnerability and adaptability of small-scale fisheries to changes in the marine ecosystem. Adaptative capacity could be explored through the natural resource dependence of fisher communities and how social and ecological aspects of communities interact to influence adaptive responses (Green et al., 2021; Monnier et al., 2020). For the West African fisheries case study, Belhabib et al. (2018)

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[16] Precisely, the mean percentage change in maximum catch potential (MCP) for 2041–2060 relative to 1991–2010 under Representative Concentration Pathway 8.5. decrease under Representative Concentration Pathway 8.5 (Liam et al. 2020)

identified the (1) movement capacity of fishers communities and their geographical extension, (2) shifting target species and (3) gear type as major keys of adaptation for artisanal fisheries. GPS tracking could inform small-scale fisheries' geographical extension and behaviour over time and space, in addition to improving fishing effort data (Behivoke et al., 2021). Studying environmental perception by artisanal fishermen is also important to understanding fishing strategies' shift motivations (Appadoo et al., 2022; Dorji et al., 2023).

For the second point, research is needed to understand interactions and coexistence between artisanal and industrial fisheries to achieve UN Sustainable Development Goals e.g., food security (SDG2), economic development to eliminate poverty (SDG1), and support effective fisheries management rules. More widely, the implementation of sustainable fisheries operations by distant-water fishing nations in the exclusive economic zones (EEZs) of many small island developing states (SIDS) and coastal states is considered by some authors to deliver significant benefits for the well-being of communities and economies in tropical countries (Lam et al., 2020). In contrast, many studies concluded that local fisheries usually provide much more benefits to coastal states than fisheries partnership agreements (e.g. FAO, 2016) In any case, the food security dependence of coastal states on distant-water fishing is a risk for coastal communities and could be an argument to ensure industrial fisheries or unsustainable practices following other criteria. For example, in February 2023, the IOTC voted a resolution to create a 72-day dFAD seasonal closure from July 2024. However, many other CPCs have objected to this resolution[17], including developing and coastal states relying economically and socially on tuna landings from industrial purse-seine fisheries (Guillotreau et al., 2023). Assessing the socio-economic telecoupling via, e.g. distant-water fishing and seafood trade, is a challenge to understand due to its complexity (Lam et al., 2020).

[17] In July 2023, at least nine states had already objected to this management measure: Comoros, Oman, Somalia (but withdrew on March 25th), Philippines, Seychelles, Kenya, European Union, France, Tanzania and Yemen.

5.4. Methods: Issues, perspectives and recommendations

5.4.1. Toward a unique indicator of the impact of fishing métier on the ecosystem

Chapter 3 provides interesting findings on pelagic fisheries indicator collinearity, complementarity, and insight into their ecological, economic and social complexity. In particular, the complementarity between species-based selectivity, sensitive species catch rate, and average trophic level of bycatch reaffirms the consideration of catch quantity (biomass) and catch quality (trophic level, species life cycle characteristics) to assess the impact of fisheries on marine ecosystem function. Increasing observer coverage of fishing fleets is necessary to achieve this catch data quality. The human observation could be coupled with electronic monitoring systems or remote electronic monitoring of catches for better scientific data collection should be considered by state members (Stobberup et al., 2021; Briand et al., 2021; Bartholomew et al., 2018). These complementarities are also studied in marine ecosystem models with explicit trophic interactions, e.g., EcoTroph, APECOSM, and EcoOcean. For exemple, in the EcoTroph model, fisheries impact could be quantified by the total primary production marine energy required (PPR) to sustain the catches and the consumption by the trophic groups. The most frequently used equation is Pauly and Christensen (1995) :

Equation 2: where Yi is the yield of species i, CR is the conversion rate of wet weight to carbon (a ratio of 9:1), TE is the transfer efficiency between trophic levels, TLi is the trophic level of species i, and n is the number of species caught. TE is frequently assumed to be around 10% (Abdou et al. 2020) but TE could be function of the TL of species (Hodgson 2022).

$$PR = \sum_{i=1}^{n} \frac{Y_i}{CR} \cdot \left(\frac{1}{TE}\right)^{(TL_i - 1)}$$

In other words, the yield is the flow, and the rest of the equation is a characterisation factor by species (CF) that removes this yield for the ecosystem. RFMO data, i.e. catch of target species and bycatch, can be used to compare this indicator of pressure on the ecosystem between fleets. Such ecosystem approaches to quantify fisheries impact emerge in RFMOs (Juan-Jordá et al., 2018).

In Chapter 2, the impact of fishing fleets on the ecosystem was linked to fishing gears and different fishing *métiers*. However, certain fishing *métier* could have various bycatch handling influencing post-release mortality of individuals, e.g. longline, gillnet, and purse seiners (Eddy, 2016; Escalle et al., 2019; Poisson et al., 2022).

To affect the PR only the part of the capture suffering the fishing mortality, we proposed to adapt the PR indicator for different fishing *métiers* j, by considering the post-release mortality rate by species and fishing *métier*:

$$\mathbf{PR} = \sum_{\mathbf{i=1}}^{\mathbf{n}} (\mathbf{Y_{i,j}} - \mathbf{Y\ release\ alive_{i,j}}) \ \ \mathbf{x} \ \ \boldsymbol{CF_i}^{(\mathbf{TL_i-1})}$$

Proposing high-quality data on discards and post-release mortality by species and fishing *métier*, particularly for high-trophic-level species, remains a significant challenge for RFMOs.

5.4.2. Exploring variability sources in Life Cycle Assessment

In Chapter 4, by comparing FAD and FSC European tuna purse seine fisheries activities (2015 – 2019), we argue that the FAD tuna has a higher climate change impact potential than the FSC tuna. This difference is not significant for all fleets, demonstrating inter-fleet variability in this period. Strictly speaking, modelling the impact by fishing strategy, by year, and by fleet would allow us to test which parameter contributes the most to each impact category of the tropical tuna harvest. Absolute values of greenhouse gas emissions from fisheries can be highly variable between years, driven by, for example, stock status, catch composition and fleet structure (métiers engaged in the fishery) (Laso et al., 2018; Hornborg et al., 2022; Chassot et al., 2021). Recommendations can be made to increase the robustness of our results. The study presented in Chapter 4 could be extended to other years of operation to assess these potential effects on environmental impacts over a more extended period. The Observatory of Exploited Pelagic Ecosystems (Ob7, IRD) has been collecting data on purse seiner activities for decades. Therefore, this study could be extended over a longer period, e.g., using an annual automatic and recursive informatics program routine.

5.4.3. Marine biodiversity and resource depletions LCA

Studying complementarity LCA with other multicriteria approaches was a part of the methodological challenge of this work to determine the convergence of the methods to assess the sustainability of fisheries, e.g. for the classification of different seafood products (Gascuel et al., 2021). Except for the impact on climate change, we could not study the convergence of both methods to assess the same impact and provide further methodological recommendations. However, the study provides indicators of biodiversity impact and the biological state of exploited resources of different tropical tuna fishing fleets, which can be compared with new approaches for assessing the biotic impact of fisheries in LCA (Gaillet et al., 2022).

Langlois et al. (2014) and Emanuelsson et al. (2014) assessed resource depletion by a distance-to-target approach based on the MSY target. Characterisation factors (CF) are proposed to quantify the impact of a unit of catch biomass. Hélias et al., (2023) provided a way of calculating CF for individual stocks based on the population dynamics model of Schaefer (1954). For example, harvesting one ton of Atlantic bluefin tuna has 5 to 25 times more impact than harvesting one ton of Atlantic yellowfin tuna (Figure 5.2). Research is on the way to propose species-based CFs of discards by the FAO ecoregion (Stanford-Clark, 2023). Testing the convergence of these methods, based on historical catch data, with our indicators on the biological status of exploited species could be interesting from an operational perspective for assessing the sustainability of seafood products.

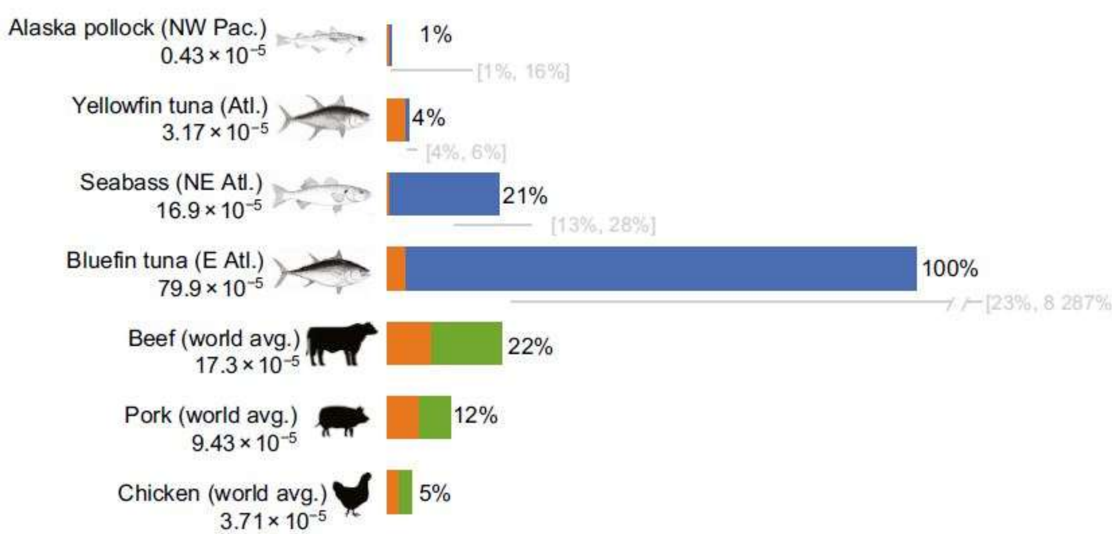

Figure 5.2: Ecosystem impact of four fisheries and three terrestrial meat production systems. Results are expressed in percentages relative to the worst system: bluefin tuna (100%). The impacts of each of them are given below the names (in species.year). Orange: sum of all ReCiPe (Hierarchist) ecosystem impact except for land use. Green: ReCiPe land use impact. Blue: fishery impact on fish stocks. Grey line: uncertainty range associated with the fishery impact on stocks. From Hélias et al. (2023)

Concerning fisheries' impact on marine biodiversity, the Global Life Cycle Impact Assessment Method (GLAM 1) recommend quantifying marine biodiversity loss with the same unit: “potentially disappeared fraction of species by year” (PDF.year), to ensure the operationalisation of research in LCIA [18] (Frischknecht et al., 2017). Biodiversity impact pathways of fisheries are grouped into four drivers of biodiversity loss: direct exploitation, land and sea-use change, climate change, and pollution (Wermeille et al., 2023). The “pollution” driver regroups various biodiversity impact potentials, e.g. eutrophication, acidification and ecotoxicity[19]. With a case study of a bottom trawling fishery, Wermeille et al. (2023) revealed that the impact on the seabed is substantial (1 × 10−9 $PDF.\ year/kglive\ weight$) [20], and that marine resource depletion and climate change are of a similar order of magnitude (2 × 10−14 $PDF.\ year/kglive\ weight$), the pollution driver being less important. Despite drivers being expressed in the same unit (PDF.year), Wermeille et al. (2023) not advised to aggregate these different pollution drivers, as they represent various levels of species disappearance, either (eco)regional or global. Constructing CFs considering spatiotemporal variability (Hélias et al., 2023), relevant type of marine biomass harvested, e.g. trophic level, species (Wermeille et al., 2023), and fishing gears (Woods and Verones, 2019) is necessary to propose pertinent LCIA for fisheries activities.

5.4.4. Common research perspectives of both approaches for fisheries management

5.4.4.1. Support to establish Harvest Control Rules

Supporting decisions using indicators is the purpose of multicriteria assessment (Lairez et al., 2020). Usually, the harvest control of marine resources is defined by a total allowable catch

[18] In Life Cycle Impact Assessment (LCIA) ‘endpoint methods’, impact categories are grouped in three areas of protection (AoP): human health, natural resources, and ecosystem quality

[19] Freshwater toxicity is not included, due to lack of harmonization of units for this impact pathway in the LC Impact method (Wermeille et al. 2023).

[20] For bottom-contact fisheries, Woods and Verones (2019) provide a method for calculating seabed impact CFs for 17 marine ecoregions in Europe, as a function of the spatio-temporal scale and intensity of the anthropogenic disturbance.

(TAC) from stock assessment and annual quota allocation to each fishery (Figure 5.3a). For decades, fisheries management has been commonly based on stock exploitation at MSY without considering the ecosystem in the TAC decision process (Kvamsdal et al., 2016). Moreover, catch history remains the principal criterion for catch allocations despite being recognised as a critical barrier to governance stability (Sinan and Bailey, 2020). Hallwood (2016) argued that the current RFMO fisheries management fails to provide an adequate framework for sustainable fishing on the high seas. For many authors, management for sustainable fisheries requires Harvest Control Rules (HCRs) using indicators of fisheries performances in addition to stock assessment models (Eide 2018; Apostolaki and Hillary 2009; Barclay et al. 2023; Curtin and Prellezo 2010; Link 2005; Kvamsdal et al. 2016; Capello et al. 2023). Setting up HCR is one major challenge for future fisheries management, an argument to deal with uncertainty and ecosystem consideration and to relieve management decisions from short-term political pressure (Kvamsdal et al. 2016; Grafton et al. 2006; Guerry et al. 2015) (Figure 5.3b). For example, bycatch caps on non-target species have already been used in the control function in North Pacific trawl fisheries targeting halibut (*Hippoglossus hippoglossus*). These caps reveal an efficient tool to address a gear-sector allocation problem; however, they were not considered tools to optimise the performance of the overall suite of fisheries in an ecosystem context (Rice and Rivard, 2007).

For the tropical tuna fisheries case study in the Indian Ocean, the current HCR on yellowfin tuna (IOTC Resolution 19/01) failed to achieve its goal as YFT catches have increased by around 9% in 2018 from 2014/2015 levels despite limitations and YFT catch limit for 2018-2020 has been exceeded in 2018 (Artetxe-Arrate et al., 2020). Therefore, quota repartition on history catches as key allocation criteria calls the equitability of resource access into question (Seto et al., 2021; Sinan and Bailey, 2020). Sinan et al. (2022) highlighted that subsidies have inflated catch histories, creating “unfair resource competition between distant water fishing nations (DWFNs) and coastal States”. In this study framework, I provide methods to select indicators for assessing the annual sustainability performances of tropical tuna fisheries, which could be a basis for research on fisheries management, e.g. scenarios of different HCRs. The indicators described and analysed can be divided into two groups: indicators dependent on common management, e.g. state of stocks targeted by the fleet, and pressure indicators linked to practices fleet-dependent, e.g. bycatch, juvenile rate, water depletion. Proposing a stakeholder consultation process to select and order fleet pressure indicators, e.g. using a decision tree and then building alternative scenarios of HCR, could be an interesting perspective to this work.

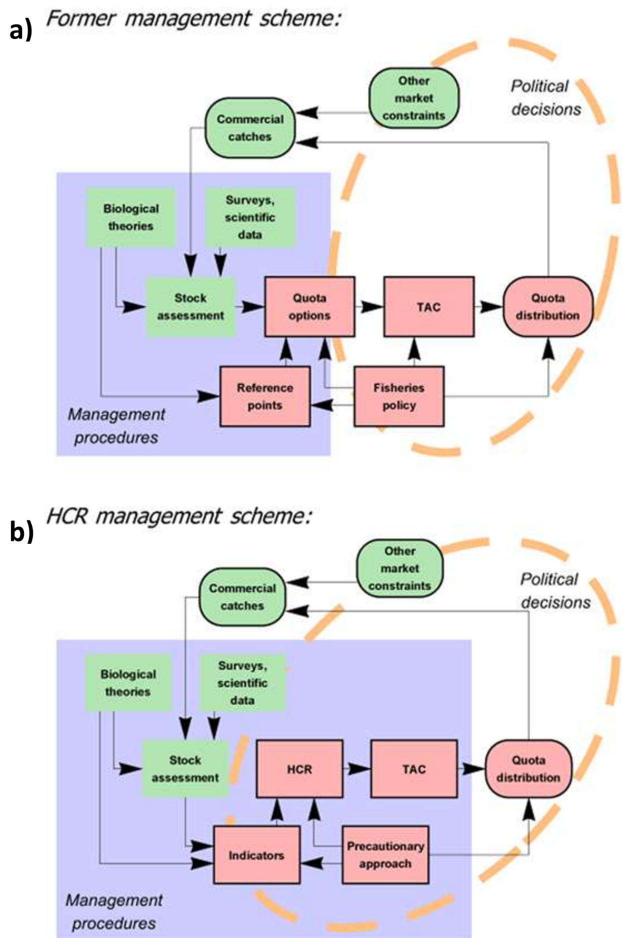

Figure 5.3: Illustration of the fisheries management system a) before and b) after introducing harvest control rules (HCR). The upper panel illustrates the system before the introduction of HCR; the lower, before the introduction of HCR. Blue boxes cover ICES related activities, dashed ovals cover the political domain, and arrows suggest information or impulse flows. TAC indicates total allowable catch. Adapted from Kvamsdal et al., (2016)

5.4.4.2. Towards change of conceptual framework for assessing sustainability

Biological productivity goals for fish stocks operationalised through Harvest Control Rules (HCRs) are central to contemporary fisheries management, which supports the fisheries economy. However, fisheries are supposed to benefit the human community by producing food, providing livelihoods, and enabling cultural continuity in the present time (FAO, 1995). Nevertheless, the lack of social data for assessing societal goals into management objectives is harmful (Symes and Phillipson, 2009; Barclay et al., 2023; Kvamsdal et al., 2016; Van Holt et al., 2016; Johnson, 2018) and is also argued by this work.

For Symes and Phillipson (2009), sustainable development "weakened the status of social objectives" because securing the needs of future generations has diverted attention from current social issues. Further, overfishing or ecological crisis may overshadow social issues, or lack of social data may explain the lack of awareness among fisheries managers (Kvamsdal et al., 2016; Symes and Phillipson, 2009). The paradox relies in part on sustainable development depending on environmental, economic, and social stability (Kvamsdal et al., 2016) linked to the conceptual framework of the 17 SDGs of the UN.

Raworth (2017) proposes a new conceptual framework of social and planetary boundaries, known as the Doughnut model (Figure 5.4), to replace social in a central place. The environmental ceiling consists of nine planetary boundaries (PB), as set out by Rockström et

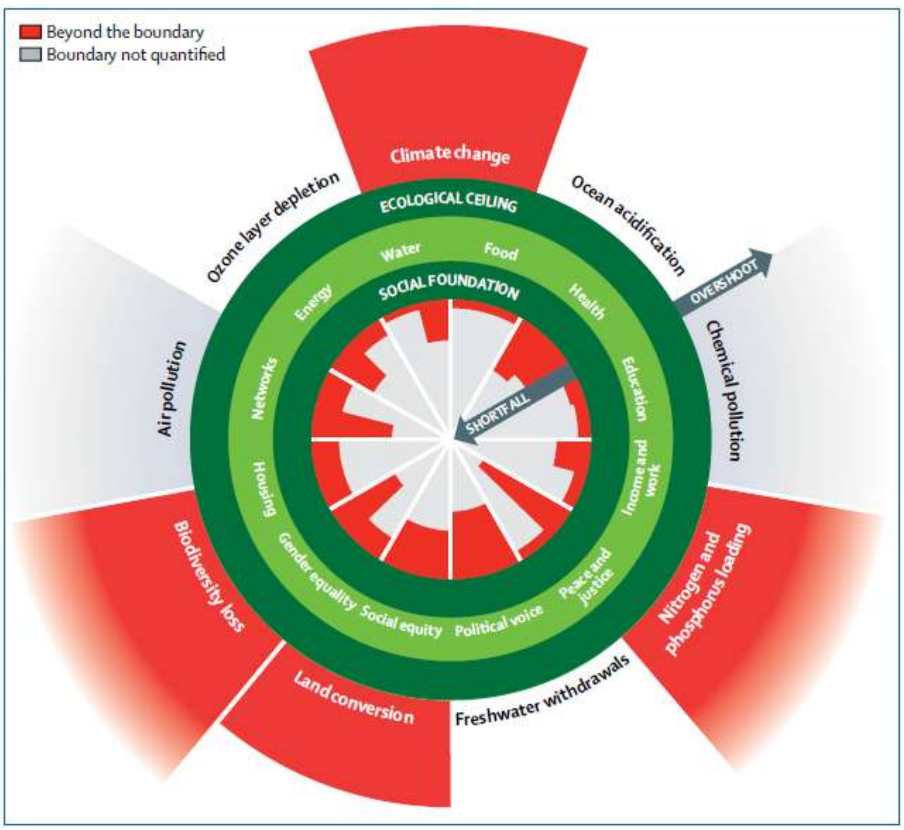

Figure 5.4: Shortfalls and overshoot in the Doughnut. Dark green circles show the social foundation and ecological ceiling, encompassing a safe and just space for humanity. Red wedges show shortfalls in the social foundation or overshoot of the ecological ceiling. The extent of pressure on planetary boundaries not currently overshot is not shown here (see appendix for all graphics). Source: Raworth (2017)

al. (2009), beyond which lie unacceptable environmental degradation and potential tipping points in Earth systems. The twelve dimensions of the social foundation are derived from internationally agreed minimum social standards, as identified by the world's governments in the Sustainable Development Goals in 2015. Between social and planetary boundaries lies an environmentally safe and socially just space where humanity can thrive.

The PB framework of Rockström et al. (2009) has enabled the development of the Absolute Life Cycle Assessment (ALCA), in which the environmental impact of a product-system is compared against a benchmark based on the earth's ecological carrying capacity to define if the system is sustainable in absolute (Ryberg et al., 2020; van Kootwijk 2020; Li et al., 2021). The functioning of these ESPs is critical to keep the earth in its stable Holocene state, which is required for anthropogenic prosperity. This conceptual framework has not yet been fully explored for marine issues, e.g. marine biodiversity losses, marine pollution, marine carbon storage (Mace et al., 2014; Baldwin and Beazley, 2019; Gonzalez-Gaya, 2021) or even fisheries' potential participation in these absolute impacts (Mouillot et al., 2023).

5.4.5. Complementarities between both methods and recommendations for fisheries management

This work's main research question was understanding the complementarities between a dashboard approach and a life cycle assessment approach for fisheries.

For decades, data-rich fisheries management followed fisheries activities to assess fishing pressure on exploited resources and, more recently, on marine ecosystems regarding biomass. Fisheries management should understand the impact of fisheries on other environmental spheres, e.g. atmosphere and hydrosphere, in a world of non-renewable resources. Not considering these other environmental impacts is a failure in their responsibility to preserve the common resource exploited, which evolves in an impacted marine environment, e.g. marine heatwave, plastic pollution (Barange et al., 2018; Smale et al., 2019; Boucher et al., 2019). The vision of the "common resource to be preserved" must extend beyond the species exploited and the pelagic waters to assess the achievement of sustainable development objectives.

The dashboard approach highlighted the potential and lack of annual data collected by RFMOs and the European Community. Before using indicators for fisheries management rules, an automatic and recursive assessment of the sustainability performance of fisheries could be performed by RFMOs or supra-regional organisations, e.g. FAO, ISSF. Setting up a sustainability working group could be an arena for the collective construction of indicators and sustainable objectives to achieve. This study proposes a workflow for calculating ecological and socio-economic indicators for tropical tuna fisheries. This work could be completed with a sensibility analysis of socio-economic indicators from the AER and for the input data of the LCA. For more relevant socio-economic indicators, RFMOs should encourage collecting socio-economic data from member states.

In the STECF, the fuel consumption data is collected for assessing energy performance as part of the economic performance of fisheries. This study reveals that this data is a reliable source for approximating the carbon footprint of European fleets. However, the fuel consumption is not the unique consumable to consider. To assess other relevant categories of environmental impact, i.e. water depletion, eutrophication and metal and mineral resource use, this study shows that an LCA routine by fishing fleets and *métiers* can be set up on the basis of fishing activity data already collected annually.

In the case of tropical tuna purse seiners, annual data important to improve for a potential future working group are bycatch and discard data by species and specific trophic level; fuel consumption of fishing and supply vessels, quantities, end-of-life and origins of materials composing FAD raft and echo-sounder buoys, fishing gears, salt and plastics. The technological development of electronic monitoring systems on board could be an opportunity to automate certain data collection and assess fisheries' sustainability performances in real-time, e.g. discards, bycatch, and the number and structure of FAD.

The complementary of the dashboard and LCA approach is already used by sustainability labels for seafood products on the market in their specifications for certification, e.g., the Swedish KRAV label. Eco-labels could include a standard of transparency for inventory data in their certification. European Union proposed a harmonised LCA method for the environmental assessment of products: The Product Environmental Footprint (PEF) method (European

Commission 2013). Moreover, ISO standards for companies and their products use LCA approaches, e.g. water footprint – ISO 14046, carbon footprint – ISO 14067. Face with such European standards, the tertiary sector, including fishing sectors, must respond more effectively to environmental sustainability challenges from production to consumer. The complementary nature of these two approaches is a key issue for the environmental labelling of seafood products. Recently, a working group of the Scientific, Technical and Economic Committee for Fisheries (CSTEP) proposed a method for environmental labelling of seafood products incorporating fisheries management indicators, LCA and a number of social indicators, leaving economic indicators to the margin (Doughnut theory). Collecting data that satisfies the dashboard and LCA approaches is a great challenge for fisheries management. Establishing a common framework for collecting company inventory data should be considered.

This work presented here proposes indicators to be retained for tropical tuna fisheries, but the method to be used to aggregate the various indicators needs to be further developed. The LCA aggregates global environmental impacts on the whole supply chain but is not spatially explicit in this study. The dashboard approach uses collecting data to assess the direct impact of fisheries, e.g. on biodiversity, biological status of exploited species, fishing company's viability or social. The search for indicators that can introduce the direct effects of fishing activities into the LCA framework, and their aggregation in Endpoint indicators (Figure 5.5), is one of the convergence areas (Wermeille, 2023). Creating spatial characterisation factors and how aggregated them is a methodological challenge. Considering the direct effects of fishing in the LCA framework is a way to ensure consumers are more responsible (Weidema et al. 2018) and support fisheries management. The relevance of these new impact indicators will need to be assessed compared with the more traditional approaches developed in the fisheries sector, e.g. the RAPFISH dashboard and fisheries standard of MSC certification. Integrating LCA indicators into dashboards is another way of convergence. Indicators can be aggregated using different ponderation ways (Lairez et al. 2020), e.g. evaluation trees (Le Féon et al. 2022). The ponderation method must be established in co-construction with the fisheries sector.

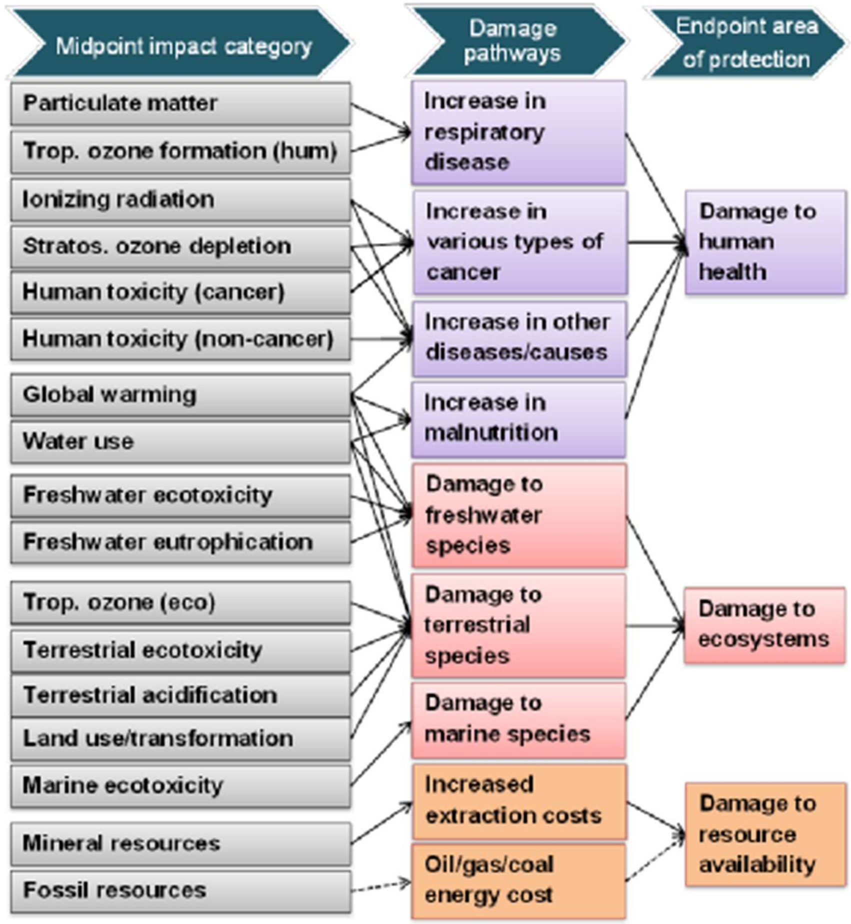

Figure 5.5: Overview the impact categories that are covered in the ReCiPe 2016 method and their relation to the areas of protection

5.5. Challenges for tropical tuna purse seiners

5.5.1. The "economic trap" of the FAD use

The dashboard approach provides a simple way of understanding an economic and ecological system's complexity and should help research orientation (Ougier et al., 2024). In Chapter 3, indicators of the dashboard provide a correlation between ecological and economic dimensions of sustainability of tropical tuna purse seiners and argue for the need to reduce the use of FAD for all environmental reasons already mentioned. However, the link between FAD use, net profit and catch is the main economic issue for FAD use reduction (Chapter 3). Purse seiner's economy and their fishermen's behaviour are driven by catch weight and not by the tuna price, which drives skippers to use FAD for its catch efficiency (Guillotreau et al., 2017). Moreover, Reyes and Airaud (2022) questioned the contribution of FAD to social sustainability. They addressed the issue of fishermen's dependence on this tool. The associated potential stress of FAD fishing seems more exciting and appreciated by fishermen than FAD fishing (Airaud Comm. Pers., 2022).

For many aspects, PS vessels remain trapped between the greater efficiency of FAD fishing and the impossibility of re-allocated the fishing effort to free schools, because skipjack tuna is mainly caught on FADs (Dagorn et al., 2013). Guillotreau et al. (2023b) theorised this “Economic trap” effect for purse seiners supplying the canning market. The authors have quantified the economic effects on the French fleet in the Indian Ocean of highly debated FAD management plans: (1) a half reduction in the number of authorized buoys per vessel, (2) a 72-day closure of FAD fishing with and (3) without re-allocation of effort on free schools. They highlighted a significant decrease in fleet profits by 7%, 10% and 18%, respectively.

A decrease in FAD use is an economic opportunity for other fisheries, e.g. longliners targeting adult bigeye tuna (Ougier et al., 2024; Guillotreau et al., 2017). The opportunity costs for other fisheries is a strong argument in negotiation by tuna RFMO stakeholders (Sinan and Bailey, 2020). However, for a two-third cut in the number of FADs, Ovando et al. (2021) estimates a net loss of US$ 3.3 billion for skipjack revenues, which is not offset by additional net present revenues of adult bigeye catch by longliners (US$ 1.9 billion). Only limited FAD removals (-15%) could produce benefits exceeding costs (Ovando et al. 2021).

One of the technical challenges, for tropical tuna purse seine fishery, is to catch skipjack while limiting the impact on the juveniles of the two other tuna species, i.e. increasing SKJ selectivity, to propose a more sustainable use of FAD (Moreno et al., 2019). To assess this specific issue and the criteria of the good biological state of exploited species, a supplementary indicator of juvenile rate on BET and YFT tuna only is justified for tropical tuna purse seines and could be added to a dashboard approach to tropical tuna purse seine sustainability.

5.5.2. Fuel use intensity by fishing strategy of purse seiners

The use of FAD has been increasing since the 90s due to the development of associated technologies, i.e.: emitting buoys and then echo-sounder buoys allowing fishermen to know the location of these devices and estimation of the aggregated biomass underneath in real-time (Lopez et al., 2014; Maufroy et al., 2016; Torres-Irineo et al., 2014), which makes this strategy highly efficient in term of catch and boat filling (Dagorn et al., 2013; Murua et al.,

2023) (Chapter 1). Recent studies focused on the Indian Ocean revealed that the FAD fishery could exhibit higher fuel consumption per ton of tuna than the free school fishery (Basurko et al., 2022; Chassot et al., 2021) using fuel consumption data. This work presents an argument in favour of this recent insight, using public data collected on the one hand, i.e. fuel use intensity based on AER data (Chapter 3), which provides a new fuel consumption database (Chapter 2), and model data on the other hand, i.e. climate change potential using Chassot et al. (2021) model (Chapter 4).

However, furthermore studies using direct consumption data need to be conducted before conclusion, due to the high variability of the boat fuel consumption between trips due to implemented strategies choices (Basurko et al. 2023). Chassot et al. (2021) highlighted that the energetic performance of the purse seine fleet quantified with the FUI had strong interannual variability. For the authors, this is mainly explained by the variability in fishing success due to a combination of variations in changes in accessibility, changes in fishing location, and changes in fishing strategy.

At a fleet scale, the high interannual variability in our FUI indicators is particularly noticed for fishing fleets in the Indian Ocean after 2017 with the fuel consumption data from the Chassot et al. (2021) model (Figure 5.6). This shift could be linked to the yellowfin tuna quota implemented in 2017, generating a transfer of effort from the FSC strategy to the FAD strategy (Báez et al., 2020). Assuming this effort report and higher FUI for FAD strategy, we could expect an increase in the FUI of European purse seiners since 2017 in the Indian Ocean, which remains unclear. For other fleets and years, the inter-annual variability of FUI is low. Additional data with higher resolution, e.g. trip or vessel, are needed to confirm any changes in the trend of fuel use intensity before concluding. To facilitate such research, enhanced monitoring of fuel consumption by fishing fleets could help and collecting vessel data consumption combined with skipper behaviour studies must be encouraged (Basurko et al., 2023), using high-resolution VMS data and fishing activities data.

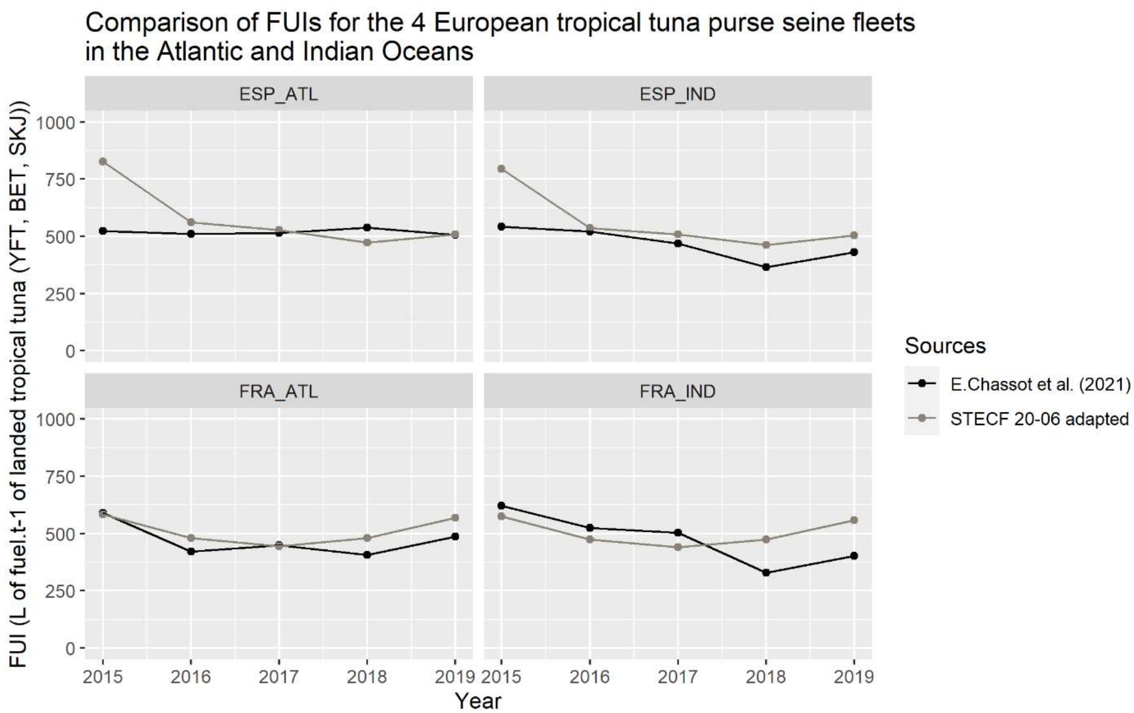

Figure 5.6: Comparison of fuel use intensity of European purse seiners by data sources (2015-2019).

5.5.3. Research perspectives: Ecological impact of management decisions in global environmental limits

For many aspects, the use of FAD by purse seiners is a key parameter for sustainable fishing activities. Spatio-temporal changes in fishing strategies are the subject of research and bio-economic scenarios to evaluate FAD management consequences on the biomass of exploited species (Perez et al., 2022; Tidd et al., 2023), on the economy of fishing fleets (Guillotreau et al., 2023b) and on the socio-economy of coastal countries (Willis and Bailey, 2020; Guillotreau al., 2023c). However, focused research on FAD management consequences on biological or economic aspects leaves out other environmental impacts, as explored by the life cycle assessment approach.

The ecological consequences of fisheries management, considering global environmental limits, are poorly understood for tuna fisheries and the fishing industry in general (Vázquez-Rowe and Benetto, 2014; Hornborg et al., 2018; Ziegler et al., 2018). The LCA is an effective approach to model fisheries management consequences (Hornborg et al., 2012). Fisheries dynamics under different management scenarios could also be completed with an LCA approach (Sigurðardóttir et al., 2014). For tropical tuna fisheries example, LCA could assess the ecological performance of FAD management scenario and their consequences on other fisheries, e.g. an effort report of FAD uses on FSC, or on longliners. An increase in longliner fishing efforts could potentially induce new constructions of longliners. As longliners have higher fuel use intensity (as could have FAD use), these effort reports may induce higher ecological impacts, e.g. on metal resource depletion and climate change potential.

Moreover, climate change may induce changes in tuna biomass and fishing location of tropical tuna purse seine fisheries (Cheung et al., 2010; Marsac 2018; Marsac et al., 2014). Using a pelagic ecosystem model (APECOSM) coupled with an economic model, Dueri et al. (2016) estimate changes[21] in the regional distribution of SKJ biomass, i.e., eastwards, and the global increase of this tuna, raising economic and profitability issues. In parallel, we must question these bioeconomic models about the ecological consequences on planetary limits. The LCA is a comprehensive tool for this purpose.

5.6. CONCLUSION

The sustainability assessment approaches developed in this study provide a strong basis for identifying main indicators to assess the sustainability of fisheries and investigate the ecologic and economic performances of tropical tuna purse seine fisheries in the Atlantic and Indian Oceans. These performances appeared mainly conditioned by fuel consumption and the fishing strategy (FSC or FAD). These results could find an application to propose Harvest Control Rules considering sustainability performance in TAC allocation for ensuring tropical tuna species, pelagic ecosystem and fishermen's wellbeing. The inclusion of multicriteria methods to assess the sustainability of fisheries as well as a dashboard and LCA to analyse

[21] Simulations on the horizon 2050 and 2095, using the Representative Concentration Pathway (RCP) 8.5, the highest emission scenario for greenhouse gas concentrations, and the Socioeconomic Shared Pathway (SSP) 3, which is characterized by low economic development and a strong increase in the world population.

performance by flag, fishing gear, or strategies looks like a natural step forward and could find a huge audience and application in fishery science.

Overall, an important conclusion of these methodological considerations is that attention should be paid to improving catch fishing data collection and developing socio-economic data collection, e.g., specific catch in weight and value, number of fishermen, and social well-being indicators. Particular attention must be paid to small-scale fleets. There is a great need to collect data on fuel consumption and maintenance of vessels and materials. In collaboration with RFMOs, fishing companies should develop ways of sharing their accounting data.

Assessing the sustainability of fisheries still has blind spots, namely, physical global impact, ecosystem impact, and social performance. Better knowledge of fisheries' impacts on physical and chemical flows, in addition to improving the data collected on biological resources, would make it possible to prioritize the efforts to be taken to achieve sustainable fisheries for future generations.

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6. ANNEXES

6.1. SUPPLEMENTARY MATERIALS OF CHAPTER 2

6.1.1. Supp. Mat. 1.1: Dashboard of indicators/attributes of sustainability performances of fisheries and criteria of selection for the analysis, based on bibliography

Dimension	Criteria	Sub-criteria	Potential indicators or information to be quantified	Indicator reference	Analysis scale	Selection result
Biological & Ecological system	Tuna stock biomass is not overexploited relative to MSY	. Stocks are not overexploited	$. \sum Yi * \left(\frac{B_i}{B_{MSY}}\right)/Yi$	Schaefer (1954); Dewals and Gascuel (2020)	Fleet	Retained
	The fleet exploits fishing stocks which are not subject to overfishing	. No stock overfishing	$. \sum \mathbf{Yi} * \left(\frac{\mathbf{F_i}}{\mathbf{F_{MSY}}}\right)/\mathbf{Yi}$	Schaefer (1954); Dewals and Gascuel (2020)	Fleet	Retained
	Fishing gears and fleet strategies minimise impact on their resources and the ecosystem	. Exploitation diagram is consistent with protection of juveniles	. High size of fish caught $. \sum \mathbf{Yi} * \left(\frac{\mathbf{F_{recrue}}}{\mathbf{F_{bar}}}\right)/\mathbf{Yi}$. Proportion of fish larger than the mean size at first sexual maturation	Pers. Comm. Fonteneau; Dewals and Gascuel (2020); SCEDUR; Pitcher and Preikshot (2001)	Fleet	Retained
		. Minimising impact on the bottom	. The gear is active or passive		Fleet	Little contrast possible
	FAD fishing is sufficiently balanced not to impact the resource or ecosystems	. FAD fishing is minimised or FSC fishing maximised	$\sum\left(\frac{\mathbf{Yi_{FSC}}}{\mathbf{Yi_{FAD}} + \mathbf{Yi_{FSC}}}\right)$	Pers. Comm. Fonteneau; Dewals and Gascuel (2020)	Fleet	Retained
	Extent and good health of critical habitats for marine resources	About critical habitats: . Sufficient presence . Good productivity . Good connectivity	. Presence, productivity, connectivity of native habitat types . Primary production . Recruitment variability	Anderson et al. (2015); Pitcher and Preikshot (2001); Kinds et al. (2016)	Ecosystem/Stock	. Limited data availability . Little contrast possible
		. Limited biological threats	. Absence of invasive species (number)			

		. Limited biological vulnerability	. Vulnerability score based on life history traits influencing a species' sensitivity to overfishing			
		. Limited abiotic threats	. No changes to the upstream watershed			
	The ecosystem can recover from disturbance or withstand ongoing pressures without collapsing	. Ecosystem biodiversity diversity is high	. Number of species . Food chain length and complexity	Anderson et al. (2015)	Ecosystem	Little contrast possible
	Presence and severity of non-fishing threats (e.g. pollution, mining), which may impede the ability of fisheries to recover	. Limited other, non-fishing threats	. Presence (Number) and severity of non-fishing threats	Anderson et al. (2015)	Ecosystem	. Offshore fisheries not affected . Little contrast possible
	Presence and severity of fishing threats other than the direct impact on the targeted stock	. Minimising the removal of un-useful biomass	. The fishery is selective . The fishery does not waste biomass . Minimum impact on the least productive biomass . Bycatch and discards concern species of low trophic level	Dewals and Gascuel (2020); SCEDUR; Juan-Jordá et al. (2018); Pitcher and Preikshot (2001)	Fleet	Retained
		. Minimising ghost fishing	. Abandoned fishing gear (number) / total fishing gear	Dewals and Gascuel (2020); SCEDUR		Limited data availability
		. Minimising macro-waste	. Macro-waste (kg) / Landings (T)			
	Existing and historical data on fisheries and existence and capacity of scientific institutions	. Capacity of institutions for data collection	. Presence of institutions and infrastructure dedicated to fisheries science . Presence of personnel trained in scientific data collection, monitoring and analysis	Anderson et al. (2015)	ORGP	Little contrast possible
		. Effective reliable and available data	. Presence of fishery-dependant data (e.g. historical catch, length-weight, sex data) . Presence of fishery-independent data (e.g. field survey data)			

	Fuel consumption data are available and consumption is minimised relative to landings	. Fuel consumption by landing tuna weight is low	. $\frac{\sum \textbf{Fuel consumed}}{\sum \textbf{Landings}\ (\textbf{all species})}$. $\frac{\sum \textbf{Carbon emitted}}{\sum \textbf{Landings}\ (\textbf{all species})}$	Chassot et al. (2021); Parker et al., (2015, 2018); Kinds et al. (2016)	Fleet	Retained
Economic system	Importance of the fisheries sector	. Fisheries sector represents a large part of national economy	. PIB	Pitcher and Preikshot (2001)	Fleet	Time needed & data not available
	Fish price and the fishing quota are stable	. Inter-annual variability of tuna price is low . Inter-annual variability of tuna quota is low	. ∑ *y* [|price *i* (Y) – price *i* (Y-1)| / price *i* (Y-1) * 100] . ∑ y [|quota i (Y) – quota i (Y-1)| / quota i (Y-1) * 100]	Dewals and Gascuel (2020); SCEDUR	Fleet/ Company	. Retained . Data not available for fleets of interest
	Fish production (Catch) is controlled and stable	. Inter-annual variability of tuna catch is low	. ∑ y [|catch i (Y) – catch i (Y-1)| / catch i (Y-1) * 100]	Dewals and Gascuel (2020); SCEDUR	Fleet/ Company	Retained
	Economic health is good and not vulnerable	. Economic productivity of energy is good	Gross added value (GAV)/ Litres of fuel consumed	Dewals and Gascuel (2020); SCEDUR	Fleet/ Company	Retained
		. Economic profitability is good	. RoFTA = Net profit / Value of physical capital . Margin rate = Gross operating profit /Gross added value			
		. Economic dependence is low (debt ratio)	Total of debts / Total assets			
		. Economic dependence is low (subvention ratio)	Operating grants / Turnover	Dewals and Gascuel (2020); SCEDUR; Pitcher and Preikshot (2001)		
		. Energetic dependence is low	Tot energy costs € / Turnover	Dewals and Gascuel	Fleet/ Company	Retained

				(2020); SCEDUR		
Socio-economic system	Work productivity is good	. Employee efficiency is good	Gross added value (GAV) / Full time equivalents (FTE)	Dewals and Gascuel (2020); SCEDUR	Fleet/ Company	Retained
	Significant revenue, not including subsidies, generated by fishermen above and beyond what they would otherwise make working at the next best alternative	. Employment is good and stable	Created FTE = FTE *Y* - FTE *Y-1*		Fleet/ Company	
		. Good salary level	Salary costs / FTE			
		. Unpaid work is lo	Value of unpaid work / Turnover			
Market & Finance system	The degree to which fishermen are paid an equitable share of the overall value of the finished product and their ability to show independence in making business decisions	. Equitable payment	. Ex-vessel price as a percentage of the export price, wholesale price, or market price	Anderson et al. (2015)	Fleet/ Company	Suitable for coastal fisheries not industrial ones
		. Independence in making business decision	. Ability of fishermen to choose buyers . Ability of fishermen to negotiate prices . Ratio of fishermen to processors/buyers			
	Ability of fish harvested in the fishery to command market prices is consistent with other fisheries or geographic areas		Price of finished product relative to other similar or identical species caught in other fisheries or geographic areas	Anderson et al. (2015)	Fleet/ Company	Scale of the study not adapted
	The systems and infrastructure in place to connect harvested fish with consumers, including the processing, distribution and scale linkages that exist along the supply chain and the efficiency of that system	. Efficient processing chain	. Ability of landed fish to reach diverse array markets . Presence and efficacy of processors . Presence and efficacy of frozen storage . Presence and efficacy of wholesalers . Rate of spoilage prior to product reaching the market	Anderson et al. (2015)	Supply chain	Scale of the study not adapted
		. Efficient distribution	. Status of transportation and logistical infrastructure . Transportation barriers to accessing desired markets			
	The ability of fishermen to exercise financial literacy skills, acquire capital that can be used to finance or negotiate vessel and fishing gear expenses at fair rates, where fishermen do not have a high level of indebtedness	. Literacy skills	. Financial literacy skills	Anderson et al. (2015)	Fleet/ Company	. Suitable for coastal fisheries not industrial ones . No data available
		. Access ability	. Willingness of financial entities to lend money to harvesters . Presence of micro-finance institutions . Presence of informal pooling or lending mechanisms . Degree to which barter or labour is used as collateral			

			. Rates of indebtedness of fishermen			
	The number of industries comprising the local economy and possibility to diversify livelihoods and supplement fishing income through other means or switch to another sector		. The number of economic sectors present in the local economy . Opportunities for diversification of income sources	Anderson et al. (2015)	Fleet/ Company	Scale of the study not adapted
	Ability to plan ahead and think far into the future, evidenced by plans and investment in the future	. Investments plans	. Evidence of investment in vessels, gear, etc. by fishermen . Evidence of investment in fishery or other community infrastructure, e.g., new docks, fish processing equipment/facilities, fish markets, new roads (in communities with fish exports), etc.	Anderson et al. (2015)	Fleet/ Company	. Scale of the study not adapted . No data available
		. Consideration of future generations	. Discussions of future generations and needed for safeguards to protect			
Governance & Management system	Nature and extent of illegal, unreported and unregulated (IUU) fishing practices	. Capacity to detect IUU fishing practices	. Presence of monitoring systems to accurately track catch . Extent of compliance with catch reporting . Comparisons of reported catch with other information sources such as market data	Anderson et al. (2015); Pitcher and Preikshot (2001); Dewals and Gascuel (2020)	Fleet	Limited data availability
		. Proof of IUU fishing practices	. Reported violations of fishery rules and regulations . Anecdotal evidence of illegal fishing			
	Existence and capacity of local stakeholder groups and organisations for management and/or advancing sustainable fisheries (e.g. fishing organisations, civil society organisations, official co-management groups)		. Existence of local organisations . Organisations currently hold responsibilities, have a clear decision-making process and deliberation process . Management bodies include meaningful representation from multiple stakeholders	Anderson et al. (2015)	ORGP	. Little contrast possible . Scale of the study not adapted
	The legal framework for the fishery, including laws, regulations and fishery management plans contain measures to allow for sustainable fisheries management	. Efficient regulatory authorities	. Enforcement and regulatory authorities are established and effective . Policies contain clear objectives & decision-making processes . Processes are established to ensure stakeholder participation . Level of implementation	Anderson et al. (2015); Dewals and Gascuel (2020)	ORGP	. Little contrast possible . Scale of the study not adapted
		. Sustainable fishery management	. Policies include measures to ensure that fishery management is accountable and transparent . Science-based management is required			

			. The fishery has a fishery management plan			
	Secure fishing rights are part of the management system and are implemented effectively	. Existent fishing rights	. Fishing rights include secure and exclusive access rights to the fishery, whether an area or portion of the catch . There are limits in place for target species	Anderson et al. (2015); Dewals and Gascuel (2020)	ORGP	Time and data needed
		. Control and management system of fishing rights	. Controls are in place on capacity and harvest . Accountability systems are in place, including monitoring and enforcement to ensure compliance with regulations			
	Presence of regulations that limit harvest (input and/or output controls) to meet management objectives		. Presence of harvest controls . Presence of clearly defined management objectives	Anderson et al. (2015)	ORGP	Little contrast possible
	Degree to which institutions are able to implement changes and adapt to changing conditions, including their commitment to sustainability and conservation		. Ability of institutions to implement changes . Institutional adaptative management processes . Institutional commitment to sustainability and conservation	Anderson et al. (2015)	ORGP	Scale of the study not adapted
	Interest and willingness of key political leaders to reform fisheries and a commitment to sustainability and conservation		. Interest in fisheries reform and commitment to sustainability/conservation . Willingness to engage with stakeholders, including conservation organisations	Anderson et al. (2015)	ORGP	Scale of the study not adapted
	Extent to which local leaders (of fishing organisations, municipalities or other structures) represent and are accountable to interests of fishery stakeholders		. Community trust in leaders and sense that leaders are good voice of community . Mechanisms to respond to feedback from participatory process or speak with interest groups	Anderson et al. (2015)	ORGP	. Scale of the study not adapted
Socio-Cultural system	Interest and active participation of stakeholders in fisheries management and evidence of social capital. Means of stakeholder participation in and influence of fisheries management decisions		. Frequency of/attendance at fisheries meetings in the community . Presence of fishery managers, enforcement officers, scientists, etc. in the community . Stakeholder engagement processes institutionalised	Anderson et al. (2015)	ORGP	No data available
	Presence of dishonest or fraudulent behaviour and extent to which it	. Level of corruption	. Country ranking on Corruption Perception Index or other national-scale corruption measure	Anderson et al. (2015);	ORGP	Time needed & Scale not adapted

	impedes/interacts with fisheries management	. Government actions	. Degree to which efforts against corruption are taken	Dewals and Gascuel (2020)		
	Role of fish or fishing in cultural rituals, identity or heritage. Extent to which fishery is a significant part of social fabric and interactions		. Festivals, art and museums related to fish or fishing	Anderson et al. (2015); Dewals and Gascuel (2020)	Fleet	No data available
	Importance of fish as a source of food/nutrition for the local community, including the proportion of local diet made up by seafood, access to alternative sources of protein, and how much fish stays in the community relative to the amount that goes to external markets.	. Importance of fish as a food source for local communities	. Percent of community members who fish for subsistence purposes . Portion of local diet made up by seafood . Security/nutrition is highly dependent on the fishery	Anderson et al. (2015)	Fleet	No data available
		. Proportion of external markets	. Percent of fish that stays in the community vs. going to regional/national/export markets			
	Degree to which there is inter- or intra- sector conflict within the fishery		. Frequency of disagreements or violence . Anecdotal accounts of conflict . Presence of conflict resolution mechanisms	Anderson et al. (2015)	ORGP/Fleet	No data available
	Ability and ease of fishermen to make decisions in the short term around fishing practices and running their business in response to changing conditions	. Regulatory flexibility	. Regulatory framework such that fishermen have flexibility in making decisions	Anderson et al. (2015)	ORGP/Fleet	No data available
		. Example of adaptations	. Demonstrated autonomy by fishermen in making business decisions . Ability to adjust fishing practices quickly and easily in response to changing environmental or market conditions			
Ecophysiology system	To know the nutritional quality of landed fish for better food safety but also to measure animal welfare through chemical markers	. Nutritional quality	. Nutrient Density Score . Microbial quality	Hallström et al. (2019); KRAV (2019); SCEDUR Project; Kinds et al. (2016)	Fleet/supply chain	No data available & scale of the study not adapted
		. Animal welfare	. Measurement of oxidative stress (thiobarbituric acid) . Presence of on-board means to reduce suffering (devices to render fish unconscious)			

6.1.2. <u>Supp. Mat. 1.2:</u> Candidate dashboard of indicators tested and data collected for the calculation

Table 2.1 : Indicator of quality of the stock assessment

<table>
<tr><th>Indicator name</th><th>Quality of the stock assessment: “stock_assessment_reliability”</th></tr>
<tr><td>Dimension</td><td>Biological & Ecological system</td></tr>
<tr><td>Sud-dimension</td><td>Qualitative stock assessment</td></tr>
<tr><td>Sub-Criteria</td><td>The fleet exploits fish stocks based on reliable stock assessment.</td></tr>
<tr><td>Indicator - Equation</td><td>

$$\sum\nolimits_{ij}(\text{Uncertainty score ij } \times \text{Eq} - \text{ICES score ij}) \times \text{Y ij}) \; / \sum\nolimits_{j}\text{Y}$$

With an uncertainty score based on coefficient of variation around F/Fmsy, Eq-ICES score = 7 - ICES score/6, Y = catch, i = species and j = fleet. The F coefficient is the fishing effort applied on the stock. The Fmsy is the F that maximizes the productivity of the stock and therefore the catches (Schaefer, 1954).
The ICES scores are based in ICES assessment categories (ICES, 2012) and was applied as follows (table 1).
Sub-table 2.1.1.: Equivalent ICES score applied for major tropical tunas (YFT - Yellowfin, BET - Bigeye, SKJ - Skipjack)
<table>
<tr><th></th><th>Score based on ICES categories</th><th>Justification</th></tr>
<tr><td>YFT Atlantic</td><td>1</td><td>Assessment based on reliable data with an advice given on an MSY (summary – stock assessment 2019)</td></tr>
<tr><td>BET Atlantic</td><td>1</td><td>Calculation of an MSY with production model projections (JABBA, MPB et SS3) (summary – stock assessment 2019)</td></tr>
<tr><td>SKJ Atlantic</td><td>3</td><td>Evaluation with forecasts and advice given on an MSY for the western stock only. Any MSY provided for the east and high uncertainties due to the life cycle of the species (summary – stock assessment 2019)</td></tr>
<tr><td>YFT Indian</td><td>1</td><td>Calculation of an MSY and projections model available</td></tr>
<tr><td>BET Indian</td><td>1</td><td>Calculation of an MSY and test of 24 models available</td></tr>
<tr><td>SKJ Indian</td><td>1</td><td>Calculation of an MSY and availability of data (compared with Atlantic SKJ)</td></tr>
</table>
The coefficient of variation around F/Fmsy is calculated from the confidence interval (CI) on the F/Fmsy, estimated by stock assessment models and available in the latest stock assessment report for major tropical tuna stocks (Yellowfin - YFT, Bigeye - BET and Skipjack - SKJ) in both Atlantic (ICCAT) and Indian Oceans (IOTC).

$$\text{Uncertainty score i} = \frac{|\,(F_i/F_i\text{msy}) - CI_i\,|}{F_i/F_i\text{msy}}$$

With i = species, F = fishing mortality, Fmsy = fishing mortality at MSY, CI= confidence interval on the F/Fmsy

The catch data per year, per fleet and per tropical tuna species are taken from the ICCAT and IOTC Task 1 data. Each fishing vessel is required to report the quantities fished by species. This declarative data is collected by each member state, aggregated by fleet and transmitted to tuna RFMOs. For the following indicators the same catch data was used unless otherwise indicated.</td></tr>
<tr><td>Unit</td><td>Dimensionless</td></tr>
</table>

Interpretation aid	The higher the score, the more the fleet is exploiting a stock whose stock assessment quality is good (Low uncertainty score).
Reference	New indicator developed on: Com. Pers. A. Fonteneau and ICES assessment categories
Data resolution	/Gear/Ocean/Year
Data source	Stock assessments and catch data from ICCAT & CTOI
Available years	Average for 2017–2019
Dataset name	Matrix A: Dashboard_all_fleets.RData

Table 2.2 : Indicator of the fishing pressure

Indicator name	The fishing pressure: "overfishing _stocks"
Dimension	Biological & Ecological system
Sud-dimension	Fishing mortality rate
Sub-Criteria	Exploitation intensity of stock from which catch originate. Fishing pressure relative to levels estimated to achieve biomass targets.
Indicator - Equation	$$1 - \sum \mathrm{Y\ ij} * \frac{\left(\frac{\mathrm{F_i}}{\mathrm{F_{MSY}}}\right)}{\mathrm{Yj}}$$ With Y = catch (ton), i = species and j = fleet.
Unit	Dimensionless
Interpretation aid	The higher the score, the less the fleet catch comes from stock overfishing (F < Fmsy). It is not a fleet contribution to overfishing indicator.
Reference	This indicator is a derivative of the Sustainable Harvest Indicator which is used in STECF (**STECF, 2017**).
Data resolution	/Gear/Ocean
Data source	The Fmsy and historic of F by major tropical tuna species were requested to ICCAT and IOTC secretariat. These parameters are stock assessment outputs. Catch data from ICCAT & IOTC.
Available years	Average for 2017–2019
Dataset name	Matrix A: Dashboard_all_fleets.RData

Table 2.3 : Indicator of the biomass status

Indicator name	The stock biomass: "stock_biomass_Bmsy"
Dimension	Biological & Ecological system
Sud-dimension	Status of marine resource populations
Sub-Criteria	Tuna stock **biomasses** are **not overexploited** relative to MSY
Indicator - Equation	$$\sum Yij * \frac{\left(\frac{B_i}{B_{MSY}}\right)}{Yj}$$ with Y = catch, i = species, j = fleet The B is the total stock biomass. The Bmsy is the stock biomass when the stock is exploited at Fmsy (Schaefer, 1954). With this indicator the following criterion is evaluated: the tuna stock biomass is not overexploited relative to MSY.
Unit	Dimensionless
Interpretation aid	The higher the score, the more the fleet participates in not overexploited stock biomass (B > Bmsy).
Reference	**Dewals and Gascuel (2020); Danto et al., (2021)**
Data resolution	/Gear/Ocean/Year
Data source	The Bmsy and historic of B by major tropical tuna species have been requested to ICCAT and IOTC secretariat. These parameters are stock assessment outputs. Catch data from ICCAT & IOTC.
Available years	1950–2019
Dataset name	Matrix A: Dashboard_all_fleets.RData

Table 2.4 : Indicator of the spawning biomass status

Indicator name	**The spawning stock biomass (relatively to SSBmsy): "spawning_ stock_biomass_SSBmsy"**
Dimension	Biological & Ecological system
Sud-dimension	Status of marine resource populations
Sub-Criteria	Tuna stock **spawning biomasses** are **not overexploited** relative to MSY
Indicator - Equation	$$\sum Yij * \frac{\left(\frac{SSB_i}{SSB_{MSY}}\right)}{Yj}$$ with Y = catch, i = species, j = fleet The SSB is the total spawning stock biomass and the SSBmsy corresponds to the stock spawning biomass when the stock is exploited at Fmsy (Schaefer, 1954). With this indicator the following criterion is evaluated: the spawning biomass of the stock is not overexploited relative to MSY. The SSBmsy and historic of SSB by major tropical tuna species have been requested from RFMOs secretariats. These parameters are stock assessment outputs.
Unit	Dimensionless
Interpretation aid	The higher the score, the more the fleet exploitation maintains the spawning biomass of the stock (SSB) at a sustainable level (SSB > SSBmsy).
Reference	**Dewals and Gascuel (2020); Danto et al., (2021)**
Data resolution	/Gear/Ocean/Year
Data source	The SSBmsy and historic of SSB by major tropical tuna species have been requested to ICCAT and IOTC secretariat. These parameters are stock assessment outputs. Catch data from ICCAT & IOTC.
Available years	1950–2019
Dataset name	Matrix A: Dashboard_all_fleets.RData

Table 2.5 : Indicator of the fished juvenile rate

Indicator name	**The fished juvenile rate: "mature_catch_rate"**
Dimension	Biological & Ecological system
Sud-dimension	Status of marine resource populations
Sub-Criteria	Exploiting diagram consistent with a protection of juveniles.
Indicator - Equation	$$\frac{\sum_j Average\ Y_i\ of\ mature\ tunas}{\sum_j Y}\ x\ 100$$ With Y = catch (ton), i = species, j = fleets. . The average Yi Mature tunas in Atlantic Ocean (AO) = $\frac{\sum N_{i,j,k}\ (L>Lm\ 50)}{\sum_{i,j,k} N}\ x\ \frac{\sum Y_{i,j,k}}{\sum_j Y}$. The Average Yi Mature tunas in Indian Ocean (IO) = $\frac{\sum N_{i,j,k}\ (L>Lm\ 50)}{\sum_{i,j,k} N}\ x\ \frac{\sum F_{i,j,FSC}}{\sum_{i,j} F}\ x\ \frac{\sum Y_{i,j}}{\sum_j Y}$ With k = fishing strategy (FSC or FAD), L mature 50 BET = 100 cm, L mature 50 SKJ = 42 cm, L mature 50 YFT = 100 cm (IO) or 115 cm (AO), n = number of sampled individuals.
Unit	Percentage
Interpretation aid	The higher the score, the more the fleet is exploiting mature fish, thus limiting its impact on stocks (Tuna length L > L with 50% of maturity)
Reference	**Dewals and Gascuel (2020)**
Data resolution	/Gear/Ocean/Year
Data source	The L mature 50 was defined based on the most recent stock assessment published (2019 for ICCAT, 2021 for IOTC). The catch data and data on length of caught tuna coming from ICCAT & IOTC.

Available years	1950–2019
Dataset name	Matrix A: Dashboard_all_fleets.RData

Table 2.6 : Indicator of the biomass impact

Indicator name	The stock biomass (relatively to B0): "stock_biomass_B0"
Dimension	Biological & Ecological system
Sud-dimension	Status of marine resource populations
Sub-Criteria	Part of the biomass of exploited stocks in the ecosystem compared to a pristine state of the stock (without fishing).
Indicator - Equation	$$\sum Yij * \frac{\left(\frac{B_i}{B_0}\right)}{Yj}$$ With Y = catch (ton), i = species, j = fleet.
Unit	Dimensionless
Interpretation aid	The higher the score, the more the fleet is exploiting a stock whose biomass is little affected by fishing (B close to B0). B0 is the virgin biomass of the stock and is estimated by the fish stock analysis (FSA). B and B0 are FSA outputs. The ratio B/Bo depends on the fishing pressure but also on the size-based selectivity of fishing. In particular, protecting juveniles allows to reduce the impact on the stock abundance.
Reference	**Dewals and Gascuel (2020); Danto et al., (2021)**
Data resolution	/Gear/Ocean/Year
Data source	FSA outputs and catch data from ICCAT & CTOI
Available years	1950-2019
Dataset name	Matrix A: Dashboard_all_fleets.RData

Table 2.7 : Indicator of the spawning biomass impact

Indicator name	The spawning stock biomass (relatively to SSB0): "spawning_stock_biomass_SSB0"
Dimension	Biological & Ecological system
Sud-dimension	Status of marine resource populations
Sub-Criteria	Part of the spawning biomass remaining after exploitation compared to the pristine state of the stock (without fishing).
Indicator - Equation	$$\sum Yij * \frac{\left(\frac{SSB_i}{SSB_0}\right)}{Yj}$$ With Y = catch (ton), i = species, j = fleet. SSB0 : virgin spawning biomass
Unit	Dimensionless
Interpretation aid	The higher the score, the more the fleet is exploiting a stock whose spawning biomass is available for the ecosystem (SSB close to SSB0).
Reference	**Dewals and Gascuel (2020); Danto et al., (2021)**
Data resolution	/Gear/Ocean/Year
Data source	Catch data from ICCAT & IOTC. SSB0 and SSB are stock assessment outputs.
Available years	1950-2019
Dataset name	Matrix A: Dashboard_all_fleets.RData

Table 2.8 : Indicator of the Free School (FSC) fishing rate

Indicator name	The Free School (FSC) fishing rate: "FSC_fishing_rate"
Dimension	Biological & Ecological system
Sud-dimension	Impact of fishing strategy on marine resources
Sub-Criteria	FAD fishing is sufficiently balanced not to impact the resource and ecosystems.

Indicator - Equation	$$\frac{\sum_j F\ on\ FSC}{\sum_j F}$$ With F = fishing effort (hours) and j = fleet. The fishing effort on FSC (hours) for purse seine fleet is available in RFMOs datasets. This data in hours is calculate by RFMOs based on the number of purse seine sets done on FSC and fishing aggregating devices (FAD).
Unit	Dimensionless
Interpretation aid	The higher the score, the lower the fleet is harvesting fish on fishing aggregation devices (FAD), what is usually considered an unstainable practice due to high impact on ecosystem (many bycatches, many sensitives species and many tuna juveniles caught), and therefore the lower the fleet have an impact on the ecosystem (High percentage of FSC fishing).
Reference	**Fonteneau et al., (2000)**
Data resolution	/Gear/Ocean/Year
Data source	ICCAT & CTOI
Available years	1950-2019
Dataset name	Matrix A: Dashboard_all_fleets.RData

Table 2.9 : Indicator of the species-based selectivity

Indicator name	**The species-based selectivity: "species_based_selectivity"**
Dimension	Biological & Ecological system
Sud-dimension	Impact of fishing strategy on marine resources
Sub-Criteria	The fishery is selective, harvesting only target species.
Indicator - Equation	$$\frac{\sum_j Y\ Targeted}{\sum_j Y}\ x\ 100$$ With Y = catch (landings + discards) (ton), j = fleet. *Table 2.8.1.: Large pelagic fishes exploitation pattern. YFT:* Thunnus albacares*, SKJ:* Katsuwonus pelamis*, BET:* Thunnus obesus*, ALB:* Thunnus alalunga*, BFT:* Thunnus thynnus*, SWO:* Xiphias gladius (see table below)
Unit	Percentage
Interpretation aid	The higher the score, the higher the fleet is selective and less is the ecosystem impact (multi-species and multi-trophic level impact) of fishing (total catch is only targeted species).
Reference	Dewals and Gascuel (2020); Danto et al., (2021)
Data resolution	/Ocean/Year (for purse seiners only)
Data source	Catch data from ICCAT & CTOI
Available years	1951–2019
Dataset name	Matrix A: Dashboard_all_fleets.RData

	Tropical waters			Temperate waters		
	YFT	SKJ	BET	BFT	ALB	SWO
Purse seine	X	X		X		
Bait boat	X	X		X		
Longline	X		X	X	X	X
Gillnet	X	X			X	

Table 2.10 : Indicator of the discard rate

Indicator name	**The discard rate: "discard_rate"**
Dimension	Biological & Ecological system
Sud-dimension	Impact of fishing strategy on marine resources
Sub-Criteria	The fishery does not waste fish biomass.

Indicator - Equation	$$\frac{\sum_j Y\ Discards}{\sum_j Y}\ x\ 100$$ With Y = catch (landings + discards) (ton), j = fleet. The discard data is available only for the Atlantic Ocean.
Unit	Percentage
Interpretation aid	The higher the score, the higher the discard volume and higher is the impact on the ecosystem (if discards are equal to the total catch).
Reference	**Dewals and Gascuel (2020); Danto et al., (2021)**
Data resolution	/Gear/Year (for Atlantic fleets only)
Data source	We selected catches categorized as discarded (live or dead) from the catch data of all species (Task 1 - ICCAT)
Available years	1986–2019
Dataset name	Matrix A: Dashboard_all_fleets.RData

Table 2.11 : Indicator of the sensitive species catches

Indicator name	**The sensitive species catches: "Sensitive_species_catch_rate"**
Dimension	Biological & Ecological system
Sud-dimension	Impact of fishing strategy on marine resources
Sub-Criteria	Minimum impact on sensitive species.
Indicator - Equation	$$\frac{\sum_j Y\ Sensitive\ species}{\sum_j Y}\ x\ 100$$ With Y = catch (ton), j = fleet. The list of conservation status species is displayed in the conservation_status_list_and_corresponding_TL.csv and referenced. For now, only sharks are considered as species with conservation status in our data set due to a lack of catch information on other potential sensitive species (rays, marine turtles, marine mammals).
Unit	Percentage
Interpretation aid	The higher the score, the higher the fleet have catch of conservation status species (sharks, rays, marine turtles, marine mammals) and therefore higher is the impact on the ecosystem (impact on both high trophic levels and the ecosystem structure).
Reference	Dewals and Gascuel (2020); Danto et al., (2021)
Data resolution	/Gear/Ocean/Year
Data source	Catch data from ICCAT & CTOI. List of conservation status species mainly from **Juan-Jordá et al. (2018)**
Available years	1950–2019
Dataset name	Matrix A: Dashboard_all_fleets.RData

Table 2.12 : Indicator of the bycatch trophic level

Indicator name	**The bycatch trophic level: "bycatch_TL_mean"**
Dimension	Biological & Ecological system
Sud-dimension	Impact of fishing strategy on marine resources
Sub-Criteria	Bycatch and discards concern species of low trophic level.
Indicator - Equation	$$\frac{\sum_{ij} Y\ (-major\ tunas) \times TL_i}{\sum_j Y\ (-major\ tunas)}$$ With Y = catch (ton), i = species and j = fleet. The bycatch is all caught species except targeted species i.e. major tunas' species (YFT, BET and SKJ). The trophic level for each species is referenced in the table conservation_status_list_and_corresponding_TL.csv.
Unit	Dimensionless

Interpretation aid	The higher the score, the less the fleet have an impact on high trophic level (TL) in the ecosystem (TL well below the keystone species TL).
Reference	**Juan-Jordá et al., (2018**)
Data resolution	/Gear/Ocean/Year
Data source	ICCAT & CTOI & List of conservation status species from Juan-Jordá et al. (2018)
Available years	1950–2019
Dataset name	Matrix A: Dashboard_all_fleets.RData

Table 2.13 : Indicator of the fuel use intensity

Indicator name	**The fuel use intensity: "fuel_use_intensity"**
Dimension	Biological & Ecological system
Sud-dimension	Chemical impact on the global climate
Sub-Criteria	The fuel use intensity by landings in weight is less.
Indicator - Equation	$$\frac{\sum_j Fuel\ consumed}{\sum_j Landings}$$ With landings of all species.
Unit	$L.kg^{-1}$
Interpretation aid	The higher the score, the higher the fleet have a potential impact on the climate change (most landings with the minimum of fuel).
Reference	**Basurko et al., (2022); Chassot et al., (2021); Parker et al., (2015); Tyedmers, (2004)**
Data resolution	/European fleet/Ocean/Year
Data source	The fuel consumption (Liter) for each fleet is not provided by tuna RFMOs. For this indicator the European data collection for European fishing fleets was used. Data are available on the STECF website and the Annual Economic Report (AER) data was considered.
Available years	2009-2019
Dataset name	Matrix B: Dashboard_european_fleets.RData

Table 2.14 : Indicator of carbon footprint

Indicator name	**The carbon footprint: "carbon_footprint"**
Dimension	Biological & Ecological system
Sud-dimension	Chemical impact on the global climate
Sub-Criteria	The carbon footprint by landings in weight is less.
Indicator - Equation	$$\frac{\sum_j \text{CO2 emission from fuel consumption}}{\sum_j Landings}$$ With landings of all species. The fuel consumed is converted to CO_2 emission (3.206 t CO_2/t fuel).
Unit	$L.kg^{-1}$
Interpretation aid	The higher the score, the higher the fleet have a potential impact on the climate change (most landings with the minimum of fuel).
Reference	**Basurko et al., (2022); Chassot et al., (2021); Parker et al., (2015); Tyedmers, (2004)**
Data resolution	/European fleet/Ocean/Year
Data source	The fuel consumption (Liter) for each fleet is not provided by tuna RFMOs. For this indicator the European data collection for European fishing fleets was used. Data are available on the STECF website and the Annual Economic Report (AER) data was considered.
Available years	2009-2019
Dataset name	Matrix B: Dashboard_european_fleets.RData

Table 2.15 : Indicator of the inter-annual variability of the tuna catches

Indicator name	**The variability in catch: "variability_catch"**
Dimension	Economic & Finance system

Sud-dimension	Production
Sub-Criteria	The tuna catch is stable over the time.
Indicator - Equation	$$\sum_j [\frac{(Catch_y - Catch_{y-1})}{Catch_{y-1}} * 100]$$ With y = year, j = fleet, catch in ton.
Unit	Percentage
Interpretation aid	The higher the indicator score, the higher the significant tuna catch fluctuates between years.
Reference	**Danto et al., (2021); Dewals and Gascuel, (2020**)
Data resolution	/Gear/Ocean/Year
Data source	Catch data were obtained from tuna RFMOs public datasets (Task 1 of ICCAT and IOTC).
Available years	2009-2019
Dataset name	Matrix A: Dashboard_all_fleets.RData

Table 2.16 : Indicator of the inter-annual variability of the tuna price

Indicator name	**The variability in YFT's prices: "Variability_YFT_prices"**
Dimension	Economic & Finance system
Sud-dimension	Economic environment (factors external to companies)
Sub-Criteria	The tuna price is stable over the time.
Indicator - Equation	$$\sum_j [\frac{(Price_y - Price_{y-1})}{Price_{y-1}} * 100]$$ With y = year, j = fleet
Unit	Percentage.
Interpretation aid	The higher the indicator score, the higher the significant tuna price fluctuates between years.
Reference	**Danto et al., (2021); Dewals and Gascuel, (2020**)
Data resolution	/Gear/Ocean/Year
Data source	Liam et al.
Available years	2009–2019
Dataset name	Matrix A: Dashboard_all_fleets.RData

Table 2.17 : Indicator of the part of energy cost

Indicator name	**The importance of energy costs: "importance_energy_costs"**
Dimension	Economic & Finance system
Sud-dimension	Economic health
Sub-Criteria	The energetic dependence is low.
Indicator - Equation	1 - (Total energy cost (€)) / Turnover (€)) The turnover is the total landings incomes (variable available in the STECF data).
Unit	Dimensionless
Interpretation aid	The higher the score, the less the energetic dependence of the fleet (turnover is much higher than the energy cost).
Reference	**Danto et al., (2021); Dewals and Gascuel, (2020**)
Data resolution	/European fleet/Ocean/Year
Data source	STECF data
Available years	2009-2019
Dataset name	Matrix B: Dashboard_european_fleets.RData

Table 2.18 : Indicator of the economic productivity of energy

Indicator name	**The energy efficiency: "energy_efficiency"**

Dimension	Economic & Finance system
Sud-dimension	Economic health
Sub-Criteria	The economic productivity of energy is good.
Indicator - Equation	Gross added value (GAV)/ litres of fuel consumed With GAV = landings incomes – total costs (without salary). The costs considered are total energy costs, total fixed costs, no fixed costs (i.e. insurance) and total repair and maintenance costs.
Unit	€.L^{-1}
Interpretation aid	The higher the score, the higher the economic productivity of energy of the fleet (most gross added value with regard to the fuel consumption).
Reference	**Danto et al., (2021); Dewals and Gascuel, (2020**)
Data resolution	/European fleet/Ocean/Year
Data source	STECF data
Available years	2009-2019
Dataset name	Matrix B: Dashboard_european_fleets.RData

Table 2.19 : Indicator of the net profit

Indicator name	**The net profit: "net_profit"**
Dimension	Economic & Finance system
Sud-dimension	Economic health
Sub-Criteria	The economic profitability is good.
Indicator - Equation	Landings incomes – total costs The costs considered are total energy costs, total fixed costs, no fixed costs (i.e. insurance), total repair and maintenance costs and salary costs.
Unit	€.L^{-1}
Interpretation aid	The higher the score, the higher the economic productivity of energy of the fleet (highest landings incomes with lowest total costs).
Reference	**Danto et al., (2021); Dewals and Gascuel, (2020**)
Data resolution	/European fleet/Ocean/Year
Data source	STECF data
Available years	2009-2019
Dataset name	Matrix B: Dashboard_european_fleets.RData

Table 2.20 : Indicator of the margin rate

Indicator name	**The margin rate: "margin_rate"**
Dimension	Economic & Finance system
Sud-dimension	Economic health
Sub-Criteria	The economic profitability is good.
Indicator - Equation	Margin rate = Gross operating profit (GOP) (€) / Gross added value (GAV) (€) With GOP = landings incomes – total costs (without salary). With GAV = landings incomes – total costs The costs considered are total energy costs, total fixed costs, no fixed costs (i.e. insurance), salary costs and total repair and maintenance costs.
Unit	Dimensionless
Interpretation aid	The higher the score, the higher the economic productivity of the fleet (most gross operating profit with regard to the gross added value).
Reference	**Danto et al., (2021); Dewals and Gascuel, (2020**)
Data resolution	/European fleet/Ocean/Year

Data source	STECF data
Available years	2009-2019
Dataset name	Matrix B: Dashboard_european_fleets.RData

Table 2.21 : Indicator of the return of tangible assests

Indicator name	The Return of Tangible Assets: "RoFTA"
Dimension	Economic & Finance system
Sud-dimension	Economic health
Sub-Criteria	The economic productivity of energy is good.
Indicator - Equation	RoFTA = gross operating profit (GOP) / Value of physical capital With GOP = landings incomes – total costs. The costs considered are total energy costs, total fixed costs, no fixed costs (i.e. insurance), salary costs and total repair and maintenance costs. Notice: For **Dewals and Gascuel, (2020**), the RoFTA have a controversial definition according to current literature. Not enough reported data by fleet to have a net profit reliable.
Unit	Dimensionless
Interpretation aid	The higher the score, the higher the RoFTA of the fleet.
Reference	**Danto et al., (2021); Dewals and Gascuel, (2020**)
Data resolution	/European fleet/Ocean/Year
Data source	STECF data
Available years	2009-2019
Dataset name	Matrix B: Dashboard_european_fleets.RData

Table 2.22 : Indicator of the work productivity

Indicator name	The work productivity: "work_productivity"
Dimension	Economic & Finance system
Sud-dimension	Economic health
Sub-Criteria	The work productivity is good.
Indicator - Equation	Gross added value (GAV)/Full time equivalent (FTE) With GAV = landings incomes – costs (without salary). The costs considered are total energy costs, total fixed costs, no fixed costs (i.e. insurance) and total repair and maintenance costs.
Unit	$€.FTE^{-1}$
Interpretation aid	The higher the score, the higher the work productivity of the fleet (most gross added value with regard to the number of full time equivalent).
Reference	**Danto et al., (2021); Dewals and Gascuel, (2020**)
Data resolution	/European fleet/Ocean/Year
Data source	STECF data
Available years	2009-2019
Dataset name	Matrix B: Dashboard_european_fleets.RData

Table 2.23 : Indicator of the created full time equivalent

Indicator name	The created Full Time Equivalent: "created_FTE"
Dimension	Economic & Finance system
Sud-dimension	Economic health
Sub-Criteria	The employment is good and stable
Indicator - Equation	Created FTE = FTE(Y) - FTE(Y-1) With Y = year, Y-1 = previous year, FTE : number of Full Time Equivalent
Unit	Number of FTE
Interpretation aid	The higher the score, the higher the created works from one year to another.
Reference	**Danto et al., (2021); Dewals and Gascuel, (2020**)
Data resolution	/European fleet/Ocean/Year

Data source	STECF data
Available years	2008-2019
Dataset name	Matrix B: Dashboard_european_fleets.RData

Table 2.24 : Indicator of the average salary of fishermen

Indicator name	The average salary of fishermen: "average_salary"
Dimension	Economic & Finance system
Sud-dimension	Economic health
Sub-Criteria	The fishermen salary level is good.
Indicator - Equation	Salary costs (€) / FTE With FTE: number of Full Time Equivalent
Unit	€
Interpretation aid	The higher the score, the higher the average salary (Most salary costs with regard to the number of Full Time Equivalent).
Reference	**Danto et al., (2021); Dewals and Gascuel, (2020**)
Data resolution	/European fleet/Ocean/Year
Data source	STECF data
Available years	2008-2019
Dataset name	Matrix B: Dashboard_european_fleets.RData

Table 2.25 : Indicator of the unpaid work – no calculed

Indicator name	The unpaid work – no calculated
Dimension	Economic & Finance system
Sud-dimension	Economic health
Sub-Criteria	The unpaid work is low
Indicator - Equation	Value of unpaid work/turnover The turnover is the total landings incomes (variable available in the STECF data). Notice: For now, not enough reported data by fleet to calculate this indicator.
Unit	Dimensionless
Interpretation aid	The higher the score, the higher the amount of unpaid work
Reference	**Danto et al., (2021); Dewals and Gascuel, (2020)**
Data resolution	/
Data source	/
Available years	/
Dataset name	/

6.1.3. <u>Supp. Mat. 1.3:</u> Disaggregation Wilcoxon tests results by effort variable tested and groups.

Bold test indicates when the difference in value induced by disaggregation is significant. (no significant: ns, p < 0.05: *, 0.01 < p < 0.05: **, p < 0.01: ***, p << 0.01: ****)

Effort variable tested as rule of disaggregation	Type of group	Group code	p	p.signif
totgtfishdays	Fishing gear	DTS	1	ns
totseadays	Fishing gear	DTS	1	ns
totfishdays	Fishing gear	DTS	1	ns
kwseadays	Fishing gear	DTS	1	ns
totkwfishdays	Fishing gear	DTS	1	ns
maxseadays	Fishing gear	DTS	1	ns
tottrips	Fishing gear	DTS	1	ns
gtseadays	Fishing gear	DTS	1	ns
totgtfishdays	**Fishing gear**	**HOK**	**1.53E-10**	****
totseadays	**Fishing gear**	**HOK**	**3.77E-09**	****
totfishdays	**Fishing gear**	**HOK**	**2.07E-09**	****
totkwfishdays	Fishing gear	HOK	0.6	ns
maxseadays	Fishing gear	HOK	0.1	ns
tottrips	**Fishing gear**	**HOK**	**6.6E-03**	**
totgtfishdays	Fishing gear	PMP	0.2	ns
totseadays	Fishing gear	PMP	0.3	ns
totfishdays	Fishing gear	PMP	0.3	ns
totkwfishdays	Fishing gear	PMP	0.2	ns
maxseadays	**Fishing gear**	**PMP**	**0.008**	**
tottrips	**Fishing gear**	**PMP**	**2.3E-03**	**
totgtfishdays	Fishing gear	PS	0.1	ns
totseadays	Fishing gear	PS	0.1	ns
totfishdays	Fishing gear	PS	0.1	ns
totkwfishdays	Fishing gear	PS	0.7	ns
maxseadays	Fishing gear	PS	0.1	ns
tottrips	Fishing gear	PS	0.1	ns
totgtfishdays	Fishing gear	DFN	0.2	ns
totseadays	Fishing gear	DFN	0.5	ns
totfishdays	Fishing gear	DFN	0.5	ns
totkwfishdays	Fishing gear	DFN	0.5	ns
maxseadays	Fishing gear	DFN	0.2	ns
tottrips	Fishing gear	DFN	0.2	ns
totgtfishdays	**Fishing gear**	**FPO**	**0.008**	**

totseadays	**Fishing gear**	**FPO**	**0.02**	*****
totfishdays	Fishing gear	FPO	0.1	ns
totkwfishdays	Fishing gear	FPO	0.6	ns
maxseadays	Fishing gear	FPO	0.3	ns
tottrips	Fishing gear	FPO	0.3	ns
totgtfishdays	Fishing gear	PGP	0.5	ns
totseadays	Fishing gear	PGP	0.5	ns
totfishdays	Fishing gear	PGP	0.5	ns
totkwfishdays	Fishing gear	PGP	1	ns
maxseadays	Fishing gear	PGP	0.5	ns
tottrips	Fishing gear	PGP	0.5	ns
totgtfishdays	**Vessel length**	**VL2440**	**1.68E-38**	********
totseadays	**Vessel length**	**VL2440**	**1.28E-53**	********
totfishdays	**Vessel length**	**VL2440**	**2.07E-57**	********
kwseadays	Vessel length	VL2440	0.09	ns
totkwfishdays	**Vessel length**	**VL2440**	**0.009**	******
maxseadays	**Vessel length**	**VL2440**	**1.48E-08**	********
tottrips	**Vessel length**	**VL2440**	**3.75E-53**	*******
gtseadays	**Vessel length**	**VL2440**	**6.49E-32**	********
totgtfishdays	**Vessel length**	**VL40XX**	**6.84E-48**	********
totseadays	**Vessel length**	**VL40XX**	**6.92E-74**	********
totfishdays	**Vessel length**	**VL40XX**	**9.07E-81**	********
kwseadays	Vessel length	VL40XX	0.1	ns
totkwfishdays	**Vessel length**	**VL40XX**	**2.72E-09**	********
maxseadays	**Vessel length**	**VL40XX**	**0.0005**	*******
tottrips	**Vessel length**	**VL40XX**	**1.03E-101**	********
gtseadays	**Vessel length**	**VL40XX**	**7.34E-29**	********
totgtfishdays	**Vessel length**	**VL0010**	**3.45E-31**	********
totseadays	**Vessel length**	**VL0010**	**6.87E-31**	********
totfishdays	**Vessel length**	**VL0010**	**2.14E-32**	********
totkwfishdays	**Vessel length**	**VL0010**	**0.0001**	*******
maxseadays	**Vessel length**	**VL0010**	**1.33E-05**	********
tottrips	**Vessel length**	**VL0010**	**2.04E-40**	********
totgtfishdays	Vessel length	VL1012	0.8	ns
totseadays	Vessel length	VL1012	0.5	ns
totfishdays	Vessel length	VL1012	0.9	ns
totkwfishdays	Vessel length	VL1012	0.07	ns
maxseadays	**Vessel length**	**VL1012**	**7.7E-25**	********
tottrips	**Vessel length**	**VL1012**	**3.9E-02**	*****
totgtfishdays	Vessel length	VL1218	0.1	ns

totseadays	Vessel length	VL1218	0.02	*
totfishdays	Vessel length	VL1218	0.02	*
totkwfishdays	Vessel length	VL1218	0.1	ns
maxseadays	**Vessel length**	**VL1218**	**2.26E-35**	********
tottrips	**Vessel length**	**VL1218**	**2.11E-02**	*****
totgtfishdays	**Vessel length**	**VL1824**	**1.88E-12**	********
totseadays	**Vessel length**	**VL1824**	**0.001**	******
totfishdays	**Vessel length**	**VL1824**	**0.004**	******
totkwfishdays	**Vessel length**	**VL1824**	**1.82E-05**	********
maxseadays	**Vessel length**	**VL1824**	**9.13E-10**	********
tottrips	**Vessel length**	**VL1824**	**3.2E-02**	*****
totgtfishdays	**Flag**	**ESP**	**0.0003**	*******
totseadays	**Flag**	**ESP**	**2.04E-05**	********
totfishdays	**Flag**	**ESP**	**2.98E-05**	********
kwseadays	Flag	ESP	1	ns
totkwfishdays	Flag	ESP	1	ns
maxseadays	**Flag**	**ESP**	**1.15E-06**	********
gtseadays	Flag	ESP	1	ns
tottrips	Flag	ESP	0.5	ns
totgtfishdays	**Flag**	**PRT**	**0.001**	******
totseadays	Flag	PRT	0.2	ns
totfishdays	Flag	PRT	0.1	ns
totkwfishdays	Flag	PRT	0.4	ns
maxseadays	**Flag**	**PRT**	**1.66E-05**	********
tottrips	Flag	PRT	0.2	ns
totgtfishdays	Flag	FRA	0.05	ns
totseadays	Flag	FRA	0.02	*
totfishdays	Flag	FRA	0.09	ns
totkwfishdays	Flag	FRA	0.4	ns
maxseadays	Flag	FRA	0.6	ns
tottrips	Flag	FRA	0.05	ns

6.2. SUPPLEMENTARY MATERIALS OF CHAPTER 3

6.2.1. *Supp. Mat. 2.1:* Dashboard of indicators/attributes of sustainability performances of fisheries and criteria selected for the analysis, based on bibliography

Refer to 7.1.1. Supp. Mat. 1.1.

6.2.2. *Supp. Mat. 2.2*: Dashboard of indicators tested and data collected for the calculation

Dimension	Indicator name	Criteria	Indicator - Equation	Interpretation aid	Reference	Data resolution	Public data source	Available years	Analysed in PCA
Biological & Ecological system	Stock assessment reliability	The fleet exploits fishing stocks based on reliable stock assessment	$\sum_{ij}(\boldsymbol{Uncertainty\ score\ ij} \times \boldsymbol{Eq} - \boldsymbol{ICES\ score\ ij}) \times \boldsymbol{Y\ ij}) / \sum_j \boldsymbol{Y}$ With an uncertainty score based on coefficient of variation around F/Fmsy and Eq-ICES score = 7-ICES score/6 and Y = catch, i = species, j = fleet	The higher the score, the more the fleet is exploiting a stock whose stock assessment quality is good (Low uncertainty score)	New indicator Com. Pers. A. Fonteneau ICES scores based on ICES assessment categories	/Gear /Ocean (Descriptor)	ICCAT & CTOI	Average for 2017–2019	Y
	Overfishing stocks	The fleet exploits fishing stocks which are not subject to overfishing	$1 - \sum \mathbf{Y\ ij} * \frac{\left(\frac{\mathbf{F_i}}{\mathbf{F_{MSY\,i}}}\right)}{\mathbf{Yj}}$ with Y = catch, i = species, j = fleet	The higher the score, the more the tuna stocks, targeted by the fleet, in proportion of catch, are overfishing.	Dewals and Gascuel (2020); Danto et al. (2021)	/Gear /Ocean /Year	ICCAT & CTOI	1963–2019	Y
	Stock biomass (relatively to Bmsy)	Tuna stock biomass is not overexploited relative to MSY	$\sum \boldsymbol{Yij} * \frac{\left(\frac{\boldsymbol{B_i}}{\boldsymbol{B_{MSY\,i}}}\right)}{\boldsymbol{Yj}}$ with Y = catch, i = species, j = fleet	The higher the score, the more the tuna stocks, targeted by the fleet, have large biomass relatively to Bmsy	Dewals and Gascuel (2020) ; Danto et al. (2021)	/Gear /Ocean /Year	ICCAT & CTOI	1950–2019	N colinear

	Spawning stock biomass (relatively to SSBmsy)	Tuna stock spawning biomass is not overexploited relative to MSY	$\sum \boldsymbol{Yij} * \frac{\left(\frac{\boldsymbol{SSB_i}}{\boldsymbol{SSB}_{\boldsymbol{MSY\,i}}}\right)}{\boldsymbol{Yj}}$ with Y = catch, i = species, j = fleet	The higher the score, the more the tuna stocks, targeted by the fleet, have large spawning biomass relatively to SSBmsy					Y
	Mature catch rate	Exploitation diagram is consistent with protection of juveniles	$\frac{\sum_j \underline{\boldsymbol{Average\ Y_i\ of\ mature\ tunas}}}{\sum_j \boldsymbol{Y}}$ With Y = catch, i = species, j = fleets, . $\boldsymbol{Average\ Y_i}$ Mature tunas (AO) = $\frac{\sum \boldsymbol{N_{i,j,k}} (\boldsymbol{L} > \boldsymbol{Lm\ 50})}{\sum_{i,j,k} \boldsymbol{N}} \ \boldsymbol{x} \ \frac{\sum \boldsymbol{Y_{i,j,k}}}{\sum_j \boldsymbol{Y}}$. $\boldsymbol{Average\ Y_i}$ Mature tunas (IO) = $\frac{\sum N_{i,j,k}\,(L>Lm\ 50)}{\sum_{i,j,k} N} x$ $\frac{\sum F_{i,j,FSC}}{\sum_{i,j} F} \ x \ \frac{\sum Y_{i,j}}{\sum_j Y}$ With k = fishing strategy (FSC or FAD), L mature 50 BET = 100 cm, L mature 50 SKJ = 42 cm, L mature 50 YFT = 100 cm (IO) or 115 cm (AO), n = number of sampled individuals	The higher the score, the more the fleet is exploiting mature fish, thus limiting its impact on stocks (Tuna length L > L with 50% of maturity)	Adapted from Dewals and Gascuel (2020)			1952–2019	Y
	Stock biomass (relatively to B0)	Participation capacity of biomass of exploited stocks in the ecosystem in a pristine state (without fishing)	$\sum Yij * \frac{\left(\frac{B_i}{B_{0\,i}}\right)}{Yj}$ with Y = catch, i = species, j = fleet We assume B0 is a proxy of the carrying capacity	The higher the score, the more the fleet is exploiting stocks whose biomass are close to the virgin state and thus available for the functioning of ecosystem	Dewals and Gascuel (2020); Danto et al. (2021)			1950–2019	N colinear

	Spawning stock biomass (relatively to SSB0)	Participation capacity of spawning biomass of exploited stocks in the ecosystem in a pristine state (without fishing) - Protection of juveniles	$\sum Yij * \frac{\left(\frac{SSB_i}{SSB_{0\,i}}\right)}{Yj}$ with Y = catch, i = species, j = fleet We assume SSB0 is a proxy of the carrying spawning biomass capacity	The higher the score, the more the fleet is exploiting stocks whose spawning biomass are close to the virgin state and thus available for the functioning of ecosystem					N colinear
	Catch on Free School	Catch rate on FSC is sufficiently important not to impact the resource or ecosystems	$\frac{\sum_j F\ on\ FSC}{\sum_j F}$ With F = fishing effort (hours), j = fleet	The higher the score, the less the fleet has an impact on stocks and on bycatch and sensitive species, and thus on ecosystem	Fonteneau (2000)	/Ocean /Year (for Purse Seiners only)	ICCAT & CTOI	1981–2019	Y
	Species-based selectivity	The fishery is selective and impacts only the target species	$\frac{\sum_j Y\ Targeted}{\sum_j Y}$ Targeted of all gears except longliners = 3 majors' tunas (YFT, SKJ, BET) Targets of longliners = YFT, BET, SWO & ALB	The higher the score, the more the fleet is selective and less non-targeted species are impacted	Dewals and Gascuel (2020); Danto et al. (2021)	/Gear /Ocean /Year	ICCAT & CTOI	1951–2019	Y
	Discard rate	The fishery does not waste biomass	$\frac{\sum_j Y\ Discard}{\sum_j Y}$ with Y = catch, j = fleet	The higher the score, the more the fleet discards biomass and the higher the ecosystem impact	Dewals and Gascuel (2020); Danto et al. (2021)	/Gear /Year (for Atlantic fleets only) (Descriptor)	ICCAT	1986–2019	Y
	Sensitive species catch rate	Minimum impact on the least productive biomass (sensitive species)	$\frac{\sum_j Y\ Sensitives\ species}{\sum_j Y}$ Conservation status species list in supplementary materials 3bis with Y = catch, j = fleet	The higher the score, the greater the fleet's catch of conservation status species (sharks, turtles) and the higher the ecosystem impact	Dewals and Gascuel (2020); Danto et al. (2021); List of conservation status species from Juan-Jordá et al. (2018)	/Gear /Ocean /Year	ICCAT & CTOI	1950–2019	Y
	Bycatch TL mean	Bycatch and discards concern species of low trophic level	$\frac{\sum_{ij} Y\ (-maj\ tunas) \times TL_i}{\sum_j Y\ (-maj\ tunas)}$	The higher the score, the less the fleet has an impact	TL by species from Juan-Jordá et al. (2018)				Y

			with Y = catch, i = species, j = fleet	on high trophic levels in the ecosystem					
	Fuel use intensity	The fuel use intensity is less by landings in weight	$1-\frac{\sum_j Fuel\ consumed}{\sum_j Landings}$ With Landings of all species	The higher the score, the more the fleet consumes fuel by kilo caught, and thus has a potential impact on climate change	Tyedmers (2004); Chassot et al. (2021); Parker et al., (2015 & 2018)	/European fleet /Ocean /Year	STECF	2008–2019	Y The most used indicator
	Carbon footprint	The carbon footprint is less by landings in weight	$\frac{\sum_j g\ CO2}{\sum_j Landings}$ With Landings of targeted species and 3.206 t CO_2/t fuel	The higher the score, the less the fleet emits the most CO2 by kilo caught, and thus has a potential impact on climate change	Basurko et al. (2022)				N colinear
Economic & Finance system	Variability in YFT's prices	Tuna price is stable: inter-annual variability of tuna price is low	$\sum_j [\frac{(Price_y - Price_{y-1})}{Price_{y-1}} * 100]$ with y = year, j = fleet	The higher the score, the more the significant yellowfin tuna price changes from one year to another	Dewals and Gascuel (2020); Danto et al. (2021)	/European fleet /Ocean /Year	STECF	2008–2019	Y
	Variability in catch	Tuna catch is stable: inter-annual variability of tuna catch is low	$\sum_j [\frac{(Catch_y - Catch_{y-1})}{Catch_{y-1}} * 100]$ With majors' tunas catches And y = year, j = fleet	The higher the score, the more the significant tuna catch changes from one year to another					Y
	Importance of energy costs	The energetic dependence is low	1-Total energy costs € / turnover	The higher the score, the lower the energetic dependence of the fleet (Lowest energy costs relative to the turnover)					Y
	Energy efficiency	The economic productivity of energy is good	Gross added value (GAV)/ litres of fuel consumed With GAV = landings incomes – costs (without salary)	The higher the score, the higher the economic productivity of energy of the fleet					Y
	RoFTA	The capital productivity is good	Net profit / Value of physical capital	The higher the score, the higher the return of tangible assets (RoFTA) of					Y

				the fleet (Highest gross operating profits relative to physical capital values)					
	Margin rate	The economic profitability is good	Gross operating profit /Gross added value	The higher the score, the higher the economic productivity of the fleet (Highest gross operating profit relative to the gross added value)					Y
	Net profit		Landings incomes – total costs	The higher the score, the higher the economic productivity of the fleet (Highest landings incomes with lowest total costs)					Y
Socio-economic system	Work productivity	The work productivity is good	Gross added value/Full time equivalents (FTE)	The higher the score, the higher the work productivity of the fleet (Highest gross added value relative to the number of full-time equivalents)	Dewals and Gascuel (2020); Danto et al. (2021)	/European fleet /Ocean /Year	STECF	2008–2019	Y
	Created FTE	Employment is stable across successive year	FTE created = FTE Y - FTE Y-1	The higher the score, the greater the number of jobs created (in full time equivalent – FTE) from one year to another. It is not the absolute number of FTE.					Y
	Average salary	Salary levels are good	salary costs/FTE	The higher the score, the higher the average salary (Greatest salary costs with regard to the number of full-time equivalents)					Y
	Unpaid work	Unpaid work is low	Value of unpaid work/turnover	The higher the indicator score, the higher the amount of unpaid work					N not enough reported data

6.2.3. ***Supp. Mat. 2.3***: Tropical tuna fishing fleet activities: main characteristics and challenges gears

This study focuses on industrial tropical tuna fishing fleets, particularly on the Spanish and French tropical purse seiner fleets. These are the two principal European fleets present together in both the Atlantic and Indian Oceans. These fleets catch three major tuna species (skipjack - SKJ, yellowfin - YFT and bigeye - BET) but mainly target skipjack and yellowfin (FAO 2020; Coulter et al. 2020).

In the Atlantic Ocean, total tuna catches have been declining since the 1990s and today attain 600 thousand tons annually, dominated by Spain (between 100 and 200 thousand tons), followed by France (less than 100 thousand tons, Supp. Mat. 2.3.1. a). In the Indian Ocean, the massive growth in catches in the 1980s and 1990s was driven largely by Taiwan (using longliners), Spain, France and Indonesia (using mostly purse seiners) (Supp. Mat. 2.3.1. b & 2.3.1. c).

Currently, the fishing effort of Spanish and French tuna purse seiners (i.e. considering only vessels under Spanish or French flags) is mainly concentrated in the eastern part of the Atlantic Ocean and in the western part of the Indian Ocean (Artetxe-Arrate et al. 2021; Kaplan et al. 2014; Le Manach et al. 2016).

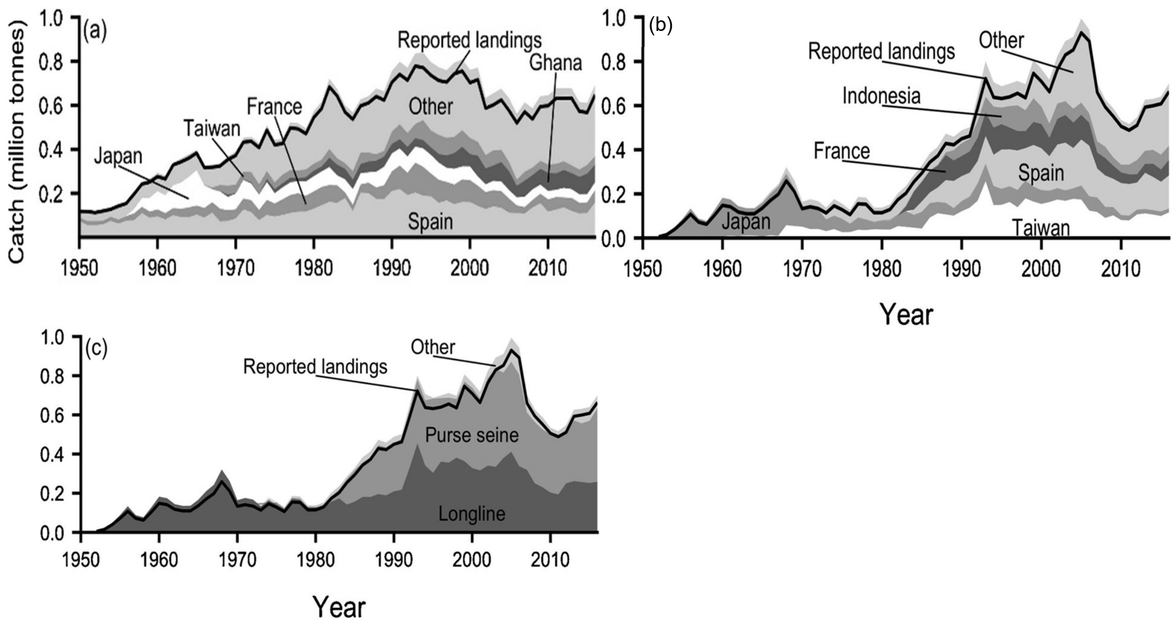
Traditionally, purse seiners catch Free School (FSC) of tuna with occasionally catch on natural floating objects (e.g. tree trunks, branches, waste) (Dupaix et al. 2022). Since the 1980s, the industrial tropical tuna fishing effort has intensified with improvements in vessel technology, such as freezer capabilities and fish aggregating devices (FADs), allowing fisheries to rapidly expand across all of the Atlantic, Indian and Pacific Oceans (Miyake et al. 2004; Majkowski 2007). Fish aggregating devices are floating objects (artificial or natural) used by fishermen to aggregate fish. They are equipped with a GPS buoy and echo sounders, which inform the fishermen about fish biomass aggregated below them (e.g., mass, fish size). Purse seiners have a concurrent use of FAD and FSC strategies. Fishing under FADs has led to a reduction in the number of null sets, which can be numerous in free school fishing. This increase in catchability and fishing effort has led to problems of fishing overcapacity as well as impacts on the ecosystem.

Over the last 15 years, following scientists' recommendations, tRFMOs have increasingly taken ecosystem issues into consideration (Garcia et al. 2003; Gaertner and Chavance 2010; Juan-Jordá et al. 2018). Ecosystem impacts are related to selectivity of fishing gear, leading to bycatch of high trophic levels and low-productivity species (i.e. long life cycle species as sharks, rays, turtles, etc.) and thus disrupting the balance of pelagic ecosystems (Cortés et al. 2010; Dagorn et al. 2013; Shelley et al. 2014). Longline and purse seine fishing are particularly concerned with this issue as these gears cause a high proportion of bycatch including high trophic level species (Murua et al. 2021). Purse seine fishing on FADs involves more bycatch species than fishing on free schools, it also leads to more fishing of yellowfin and bigeye juveniles and potentially modifies tuna migration routes by acting as an 'ecological trap'

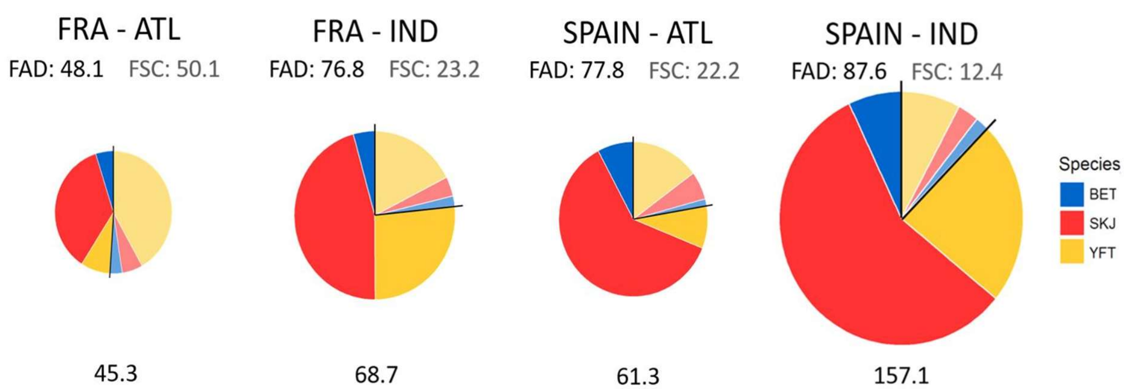
(Dagorn et al. 2013; Murua et al. 2021). The spatial distribution of tuna species could be affected, with impacts on the size of tuna schools (Sempo et al. 2013). For reasons, FAD or FSC fishing proportion is usually monitor for qualifying potential ecological impact of purse seine fisheries (Fonteneau 1997; Dagorn et al. 2013; Murua et al. 2021). The tRFMOs have to deal with additional aspects. Tropical tunas have a particular stock dynamic (large spatial migration scales) which is still not well known and causes difficulties for stock assessment and management (Kaplan et al. 2014).

Currently, catches under FADs represent about 45% of catches of the three major tuna species by the French and Spanish fleets in the Indian Ocean and the Spanish fleet in the Atlantic Ocean. In the Atlantic Ocean, the French fleet alone catches more than a half of the three major tuna species fished on free schools (Supp. Mat. 2.3.2.).

6.2.3.1. <u>Supp. Mat. 2.3.1:</u> Catches of tuna and large pelagics in the Atlantic (a) and Indian (b, c) Oceans from 1950 to 2016, by a) b) fishing country (107 and 54 additional countries are pooled in 'Other' for Atlantic and Indian Oceans, respectively); and c) fishing gears (5 additional gear categories are pooled in 'Other' for Indian Ocean) (adapted from Coulter et al. 2020)



6.2.3.2. <u>Supp. Mat. 2.3.2:</u> Table S1-B Recent average (2015–2019) species composition of European purse seiner fleet catches of main tropical tuna species (x1000 T) by fishing strategy. Free school (FSC) fishing is shown in strong colors and use of fish aggregating devices (FAD) in pastel colors. Species: Bigeye (BET), Skipjack (SKJ) and Yellowfin (YFT) tunas. Data sources: ICCAT and IOTC Task 2 catches



6.2.4. *Supp. Mat. 2.4*: Details on data collection and calculation of indicators.

6.2.4.1. Supp. Mat. 2.4.1: Synthesis of Ougier et al.'s (In Press) materials and methods.

The tuna fishing fleets considered were composed of industrial fishing vessels (length greater than 40 metres). The industrial fleets represent 78% and 62% of catch in average (2015-2019) in the Atlantic and Indian Oceans respectively (D. Pauly, Zeller, and Palomares 2020).

Our goal was to gather data on multiple tuna fishing fleets for a maximum of years. To achieve this, we focused our analysis on indicators that could be calculated based on two collection frameworks: the tRFMO catch data collections and the socio-economic fleet data collections of the Scientific, Technical and Economic Committee for Fisheries (STECF - stecf.jrc.ec.europa.eu) of the European Union. Public data from the tRFMOs and STECF was collected directly from their respective websites.

In the Atlantic and Indian Oceans, the tRFMOs are the International Commission for the Conservation of Atlantic Tunas (ICCAT - www.iccat.int) and the Indian Ocean Tuna Commission (IOTC - iotc.org). These tRFMOs collect and archive various data annually from member states, including fleet effort, catches and landings by species. Historical data on stocks (biomass, virgin biomass, spawning biomass, fishing effort from stock assessment) were obtained on demand from the RFMO secretariats. Stock assessment parameters (fishing effort at MSY, biomass and spawning biomass at MSY, maturity size, virgin biomass and spawning biomass) were collected from the most recent stock assessment published by the tRFMOs (YFT: ICCAT (2019), IOTC (2017); SKJ: (ICCAT (2022), IOTC (2017c); BET: ICCAT (2018), IOTC (2017b)). Following stock assessment reports, virgin biomass and spawning biomass estimations consider carrying capacity of the ecosystem (K). The density dependant effects are not considered for now and provide supplementary uncertainty on the B0 and SSB0. ICCAT and IOTC do not conduct evaluations on stock assessment reliability. Only ICCAT provides information of the quality of data reported by each country, which is insufficient to ensure the reliability of stock assessments in both Atlantic and Indian Oceans. ICES has defined assessment categories that are suitable for tuna stock assessment using a decision tree (ICES 2012).

A common data frame was created, which for each tuna fishing fleet in each ocean collected the specific catches, landings and discards when the data was available. Based on this data frame, we were able to calculate 14 ecological indicators for 59 in the Atlantic Ocean and 43 tuna fishing fleets in the Indian Ocean (Table 2.1).

From the STECF website (https://stecf.jrc.ec.europa.eu/reports/economic), we obtained the Annual Economic Report (AER, version 20-06) data at fleet segment scale, from 2008 to 2019. From this report we selected fleets working in the supra region named 'Other Fishing Region' (OFR), with geographical indicators IWE (International Waters Exclusively), NEU (Non-

European Waters) or NGI (No Geographical Indicator), in FAO areas 51, 57 (Indian Ocean), 34 and 47 (tropical Atlantic Ocean) and with purse seines as the fishing gear.

In the AER data, the socio-economic results are summed (aggregated) for all vessel length segments (cluster) of the Spanish fleet, in 2012. It is necessary to correct this aggregation, which could lead to a bias (overvaluation or devaluation) in the economic performance of this fleet in 2012. Only effort data are not clustered in the AER data. We assume than the economic and socio-economic results are proportionate to the fishing effort of the segment of fleet. Assuming this hypothesis, the fishing effort of the vessel segment larger than 40m can be compare to the sum of fishing effort for all vessel segment to estimate the part of the vessels larger than 40 m in the economic and socio-economic results. The fishing effort metric (in kW-days) of the vessel segment larger than 40 m represents to 98% of total fishing effort of the cluster (i.e. the sum of fishing effort for all vessel segment of the Spanish fleet, in 2012). The choice of effort metric was tested and validated by Ougier *et al.* (In Press). We multiply each economic and socio-economic variable results of the AER data by 0.98 (98%) for of the Spanish fleet, in 2012, to provide comparable data between years and fleets. After this correction, only vessels larger than 40 m are retained.

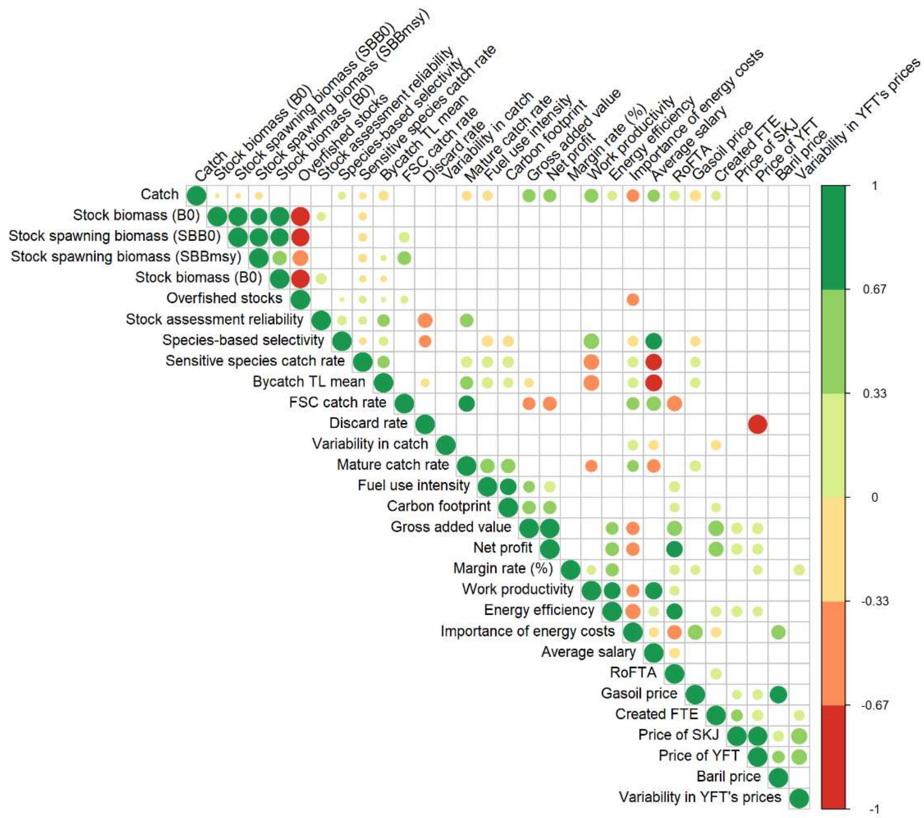
The socio-economic variables of the STECF were available for a very low geographic resolution corresponding to all oceans together (Other Fishing Region scale). We allocated socio-economic data to each ocean proportionally to the total catch by FAO area, including targeted tropical tuna and bycatch species (Supp. Mat. 2.4.2). Based on these socio-economic variables, we calculated seven economic indicators, three socio-economic indicators of fisheries performances (Table 3.1). For the European tuna fleets (French and Spanish purse seiners), we added these eight socio-economic indicators to the initial ecological-indicator data frame. The results of these indicators and additional details on the calculation methods are available in the associated data paper Ougier *et al.* (In Press). Data and RMarkdown code (R and R studio software) are available on a data repository (https://doi.org/10.57745/Z0PH0Q) and can be explored via associated Shiny app (http://halieut.agrocampus-ouest.fr/discardless_app/acv_dashboard/).

6.2.4.2. <u>Supp. Mat. 2.3.2:</u> Table explaining the allocation of socio-economic data (AER data) to each ocean based on landings data by FAO area in weight (average proportions from 2008 to 2019)

	Atlantic Ocean Tuna fleet	Indian Ocean Tuna fleet	Pacific Ocean Tuna fleet	Other fleets
French fleet	44.3%	55.7%	0%	~4%
Spanish fleet	27.7%	57.2%	15.1%	~4%

6.2.5. Supp. Mat. 2.5: Correlation matrix between indicators from the dashboard and economic environment variables e.g., price of yellowfin tuna, gasoil price.

The gradient of colour corresponds to the r of Pearson correlation (positive correlation r = 1; negative correlation r = -1). The size of circle corresponds to the test significance.

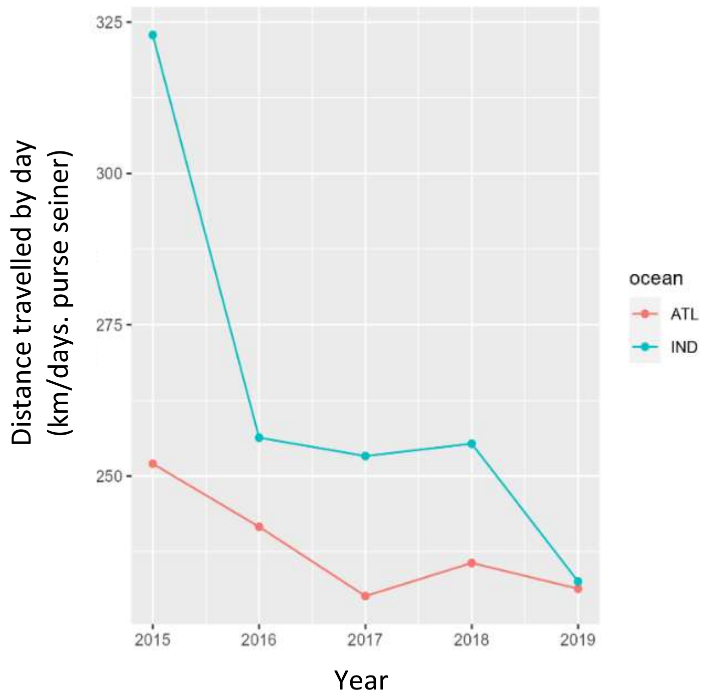


6.3. Supplementary materials of chapter 4

6.3.1. Supp. Mat. 3.1: Number of national active vessels and active supply vessels for each fleet and year, and associated major tropical tuna landing (10^3 Ton)

Year	French – Atlantic O			Spain – Atlantic O			French – Indian O			Spain – Indian O		
	PS	SV	Landing Ob7/ICCAT	PS	SV	Landing ICCAT	PS	SV	Landing Ob7/IOTC	PS	SV	Landing IOTC
2015	9	1	43.2 / 42.7	12	2	64.2	12	2	53.4 / 54.2	17	13	120.7
2016	11	1	46.8 / 48.1	10	2	66.7	12	2	66.7 / 68.0	14	16	136.1
2017	10	1	43.9 / 44.5	10	3	64.2	12	3	68.4 / 66.8	14	13	151.3
2018	10	1	50.7 / 50.2	10	5	54.9	12	4	84.4 / 84.5	14	12	202.1
2019	10	1	42.8 / 41.6	10	4	56.6	12	5	71.9 / 70.4	15	9	172.7
Average	**10**	**1**	**45.5 / 45.4**	**10.4**	**3.2**	**61.3**	**12**	**3.2**	**69 / 68.8**	**14.8**	**12.6**	**156.6**
Sd	0.7	0	3.3 / 3.7	0.89	1.3	5.2	0	1.3	11.1 / 10.8	1.3	2.5	31.9

6.3.2. <u>Supp. Mat. 3.2:</u> Average distance travelled by vessels by days at sea in both Atlantic (ATL) and Indian (IND) Oceans.



6.3.3. <u>Supp. Mat. 3.3:</u> Description of the fuel data set. Number of vessels and total weigth (t) of fuel delivered annually to the purse seiners (PS) and support vessels (SV) that called on Port Victoria, Seychelles, during 2015-2019 (adapted from Chassot et al. 2021).

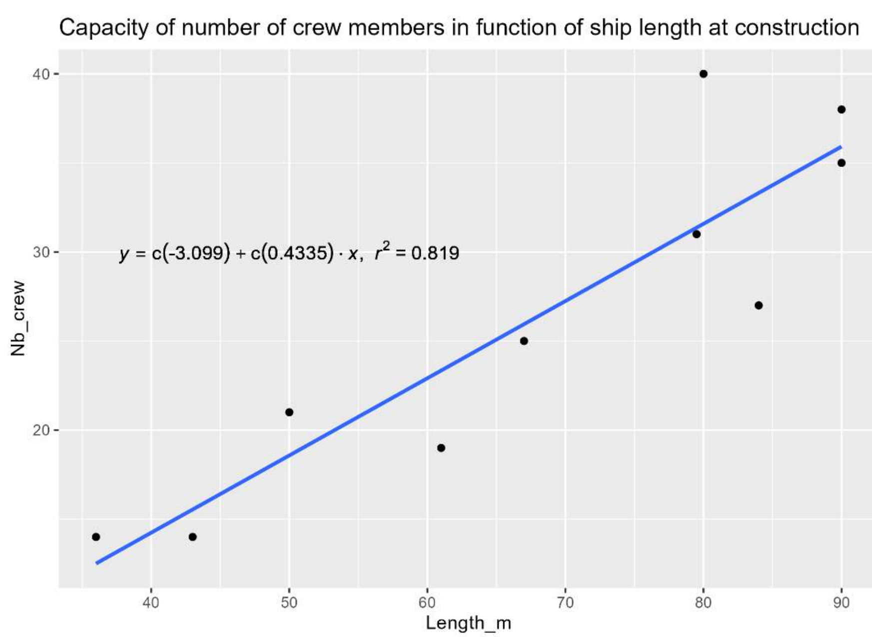
Year	VesselType	Vessels	TotalWeight	Percentage of supply vessel consumption (%) $= \left(\frac{Total\ weigth_{SV}}{Vessels_{SV}} \Big/ \frac{Total\ weigth_{PS}}{Vessels_{PS}} \right) x\ 100$
2015	PS	49	149,043	14.7
2015	SV	18	8099	
2016	PS	47	166,227	13.6
2016	SV	21	10,103	
2017	PS	45	146,588	15.5
2017	SV	20	10,611	
2018	PS	44	143,095	15.2
2018	SV	18	8932	
2019	PS	45	141,735	17.6
2019	SV	16	8889	
Average				15.3 ± 1.5

6.3.4. <u>Supp. Mat. 3.4.:</u> Data used for estimation of number of crew member.

6.3.4.1. <u>Supp. Mat. 3.4.1:</u> Data collection from PIRIOU website.

Vessel type	Length (m)	Number of maximal crew member
Saint Antoine Marie II	43	14
Tuna freezer purse seiner	61	19
Avel Vlad	67	25
Glénan	84	27
Franche-Terre	90	38
Morn Seselwa	80	40
PS 36-205	36	14
PS 50-600/760	50	21
PS 90-1900/2150	90	35
PS 80-1620/1800	79.5	31

6.3.4.2. <u>Supp. Mat. 3.4.2:</u> Linear relation between vessels maximal capacity of fishermen on board and vessels length.



6.3.5. <u>Supp. Mat. 3.5:</u> Eco Invent processus and flow parameters used in the study. This annexe specify Eco invent processus when there differs from the inventory presented in Cloâtre (2018) from the ICV-Pêche project.

6.3.5.1. Supp. Mat. 3.5.1: Table of processus called in SimaPro and associated uncertainty (refer to the database sources)

<table>
<tr><th colspan="2">Processus name</th><th>Processus name in database</th><th>Source</th></tr>
<tr><td colspan="2">Average purse seine boat</td><td>Average boat YFT/FR U</td><td rowspan="4">Agribalyse Database:
From ICV-Pêche: Cloâtre (2018)</td></tr>
<tr><td colspan="2" rowspan="2">Fishing gear, seine</td><td>Seine, 1600-220m/FR U</td></tr>
<tr><td>Seine, 1600-220m/FR U</td></tr>
<tr><td colspan="2">Average supply vessel</td><td>Average boat YFT/FR U</td></tr>
<tr><td colspan="2">Skiff</td><td>Steel, low-alloyed, hot rolled {RER}| Cut-off, S</td><td rowspan="4">EcoInvent Database</td></tr>
<tr><td colspan="2">Seine transport</td><td>Transport, freight, sea, container ship {GLO}|market for transport, freight, sea, container ship | Cut-off, S</td></tr>
<tr><td colspan="2">Salt transport</td><td>Transport, freight, sea, container ship {GLO}| market for transport, freight, sea, container ship | Cut-off, S</td></tr>
<tr><td colspan="2">Crew airplane transport</td><td>Transport, passenger aircraft, long haul {GLO}|market for transport, passenger aircraft, long haul | Cut-off, S</td></tr>
<tr><td rowspan="2">FAD raft</td><td>Stealth raft:
.Metallic floating structure
.Canvas for cover the structure
.Main rope and rope attractors
.Floats</td><td>. Steel, low-alloyed, hot rolled {GLO}| market for | Cut-off, S
. Polyvinylchloride, bulk polymerised {GLO}| market for | Cut-off, S
. Polypropylene, granulate {GLO}| market for | Cut-off, S
. Ethylene vinyl acetate copolymer {RoW}| market for ethylene vinyl acetate copolymer | Cut-off, S</td><td>BioFAD-project: structure corresponding to stealth raft</td></tr>
<tr><td>Echosounder buoy</td><td>Satellite buoy, for tuna fishing on FADs/FR U</td><td>Agribalyse Database:
From ICV-Pêche: Cloâtre (2018)</td></tr>
</table>

6.3.5.2. Supp. Mat. 3.5.2. Table of parameters uncertainty noted by authors.

Pedigree-matrix is a qualitative uncertainty assessment: {Completeness, Reliability, Temporal Validity, Spatial Validity, Consistency} with note from 1 (achieved) to 5 (no achieved). The Pedigree matrix is adapted to mathematic uncertainty in SimaPro software (Ciroth et al. 2016).

Processus name	Parameter	Uncertainty	Source
FAD raft	For all parameters used: weight, FAD dimension, etc.	Pedigree matrix {3,3,2,1,1, na}	BioFAD-project: structure corresponding to stealth raft
Skiff life span	Life span (years)	Pedigree-matrix: {4, 4, 2, 1, 2, na}	Com. Pers. ORTHONGEL
Salt consumption rate	Rate (kg of salt/ T landing tuna)	Pedigree-matrix: {1,2,1,1,2, na}	Data from CFTO company
Crew turnover	National crew (french or spanish	Pedigree-matrix: {3,2,1,3, na, na}	Com. Pers. ORTHONGEL and CFTO company
	No-national crew		
Travel distance in airplane	Travel distance in airplane	Pedigree-matrix: {2,2,1,1,1, na}	Distance calculated from fr.distance.to

6.3.6. Supp. Mat. 3.6: Comparison of LCA impact assessment between the average tropical tuna produced by European purse seiner fleets between 2015 and 2019 and the literature review considering different functional units.

To convert impact by kg of tuna in impact by 100g of protein, we assume a tuna protein rate of 24% for the three species (Peng et al. 2013).

Impact categories	Average European tropical tuna	Compared protein resources			Sources
		tuna	seafood	meat	
Climate change (kg eqCO2/kg) **(kg eqCO2/100g protein)**	1.65 ± 0.09 **68*10^-2 ± 4*10^-2**	1.3 ± 0.2* **54*10^-2 ± 8*10^-2** (purse seiners)	1-86 **4 – 12***** **(farmed)**	4 – 129** **3 - >75*****	*Hospido and Tyedmers (2005) **Nijdam, Rood, and Westhoek (2012) *** Poore and Nemecek (2018)
Acidification (mol H+ eq./kg) **(mol H+ eq./ 100g protein)** or *(g SO2 eq./kg)* ***(g SO4 eq./100g protein)***	4.4 ± 0.7 **1.8 ± 0.3** or *35 ± 2* ***14.6 ± 0.8***	/ or 14 ± 3* **6 ± 1** (purse seiners)	/ or * ***20 – 40****** ***(farmed)***	/ or *3 - 65*** ***40 - >150******	Or **Hospido and Tyedmers (2005) **De Vries and De Boer (2010) *** Poore and Nemecek (2018)
Eutrophication, freshwater (g P04 3- eq./kg) **(g P04 3- eq./100g protein)**	29.10^-2 ± 2.10^-2 **121*10^-3 ± 8*10^-3**	2.8 ± 0.4* **1.2 ± 0.2** (purse seiners)	**20g – 130g**** **(farmed)**	**3 - >75****	* Hospido and Tyedmers (2005) ** Poore and Nemecek (2018)
Eutrophication, marine (g N03- eq./kg) **(g N03- eq./100g protein)**	41 ± 3 **17 ± 1**	/	478 ± 4* (salmon farmed) 49** (conventional common carp)	(New zeland beef)	* Song et al. (2019) **Biermann and Geist (2019)
Water use (kL or m3/kg) **(kL or m3/ 100g protein)**	61.10^-3 ± 5.10^-3 **25*10^-3 ± 2.10^-3**	/	**0 - 50**** **(farmed)**	**0 - >100****	** Poore and Nemecek (2018)
Ozone depletion (g CFC 11 eq./kg) **(g CFC 11 eq./100g protein)**	36.10^-5 ± 2.10^-5 **150.10^-6 ± 4.10^-6**	120.10^-5 ± 20.10^-5* **5.10^-3 ± 8.10^-4** (purse seiners)	5.8.10^-4** (conventional common carp)		* Hospido and Tyedmers (2005) **Biermann and Geist (2019)

6.3.7. Supp. Mat. 3.7: Major tropical tuna (YFT, BET and SKJ) and other species (ALB, LTA, FRI, OTH) landings of French PS fleets (average between 2015 and 2019) in ton and percentage. Data source: Observatory of exploited pelagic ecosystems (Ob7, IRD).

Ocean	Strategy	SKJ (T)	YFT (T)	BET (T)	ALB (T)	FRI (T)	LTA (T)	OTH (T)	TOTAL (T)
ATL	FAD	16,080 (71 %)	3,619 (16 %)	2,244 (9.9 %)	10.9 (0.05 %)	527 (2.3 %)	178 (0.8 %)	0.02	22,660
		96.9 %			**3.1 ± 1.5%**				
	FSC	2,593 (11 %)	19,335 (81.9 %)	1,613 (6.8 %)	43.3 (0.18 %)	24.8 (0.1 %)	7.78 (0.03 %)	0.624	23,617
		99.7 %			**0.3 ± 1.3%**				
IND	FAD	31,376 (59.3 %)	18,444 (34.9 %)	2,989 (5.6 %)	53.4 (0.1 %)	0	0	54 (0.1 %)	52,917
		99.8 %			**0.2 ± 0.1%**				
	FSC	2,590 (16 %)	12,229 (75.2 %)	1,347 (8.3 %)	95.2 (0.6 %)	0	0	0.246	16,262
		99.5 %			**0.5 ± 0.4%**				

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Titre : Évaluation de la durabilité écologique et socio-économique des pêcheries. Application aux pêcheries thonières tropicales à la senne.

Mots clés : multicritère, tableau de bord, analyse de cycle de vie, gestion des pêches, indicateurs

Résumé : Améliorer la durabilité des pêcheries nécessite d'évaluation leur performance écologique, économique et sociale. Une approche tableau de bord d'indicateurs de durabilité et une approche par Analyse de Cycle de Vie sont conduites sur le cas des pêcheries thonières tropicales à la senne. La thèse vise à comprendre dans quelles mesures ces deux approches peuvent être complémentaires et quelles sont les propositions qui peuvent en être déduite pour une gestion durable des flottilles.

Le tableau de bord d'indicateurs montre la complémentarité entre l'évaluation de la performance écologique des flottilles sur les écosystèmes et sur les stocks exploités. L'ACV complète le tableau de bord avec des indicateurs d'impact potentiel sur les ressources en eaux, en métal et minerais, sur le changement climatique et sur la couche d'ozone. Évaluer les impacts liés aux fins de vie des plastiques rejetés en mer par les pêcheries reste un défis méthodologique majeur. La durabilité économique des thoniers senneurs repose sur l'utilisation de dispositifs de concentration de poissons, et semble être en conflit avec leur durabilité écologique et sociale. L'utilisation des DCP est source de pollution supplémentaire pour ces flottilles et induit un risque d'impact sur les écosystèmes (e.g., captures d'espèces sensibles, de juvéniles de thon albacore et de thon obèse).

Plus de données socio-économiques sont nécessaires pour répondre aux enjeux d'évaluation de performance de durabilité des pêcheries.

Title: Assessing the ecological and socio-economic sustainability of fisheries. Application to tropical tuna purse seine fisheries.

Keywords: multicriteria, dashboard, life cycle assessment, fisheries management, indicators

Abstract: Improving the sustainability of fisheries requires assessing their ecological, economic, and social performance. In the case of tropical purse seine tuna fisheries, a dashboard approach with sustainability indicators and a life cycle assessment (LCA) approach are used. The thesis aims to understand how these two approaches can be complementary and what proposals can be deduced to manage fleets sustainably.

The dashboard of indicators shows the complementarity between the assessment of the ecological performance of fleets on ecosystems and exploited stocks. LCA supplements the dashboard with indicators of potential impact on water resources, metals and minerals, climate change and ozone layer depletion. Assessing the impacts related to the end-of-life of plastics discarded at sea by fisheries remains a major methodological challenge. The economic sustainability of purse seine tropical tuna fleets relies on using fish aggregating devices (FADs), which seems in conflict with their ecological and social sustainability. The use of FADs results in additional pollution for these fleets and impact risks on ecosystems (e.g., catches of sensitive species, juvenile albacore tuna, and obese tuna).

More socio-economic data is needed to address the challenges of assessing the sustainability performance of fisheries.