Evaluation des impacts environnementaux du chalutage de fond et de l'aquaculture en Tunisie : approche comparative par les Analyses de Cycle Vie (ACV)

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Thèse soutenue le 14 Décembre 2017

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A Brest le 14 Décembre 2017

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Jury

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Résumé

L'aquaculture et la pêche impactent l'environnement, les ressources et le fonctionnement des écosystèmes. L'un des enjeux en écologie est de placer ces activités anthropiques dans un cadre de développement durable, en améliorant leurs rentabilités économiques, leurs attractivités sociales et leurs bilans environnementaux. Du fait des besoins en ressources croissants, les impacts sur l'environnement sont de plus en plus décriés. Afin de quantifier et de limiter ces impacts, différentes méthodes d'évaluation environnementale ont vu le jour. L'Analyse de Cycle de Vie (ACV) est une méthode pertinente pour évaluer le bilan environnemental d'un produit en prenant en compte l'ensemble de ses étapes de vie, "du berceau à la tombe", depuis l'extraction des matières premières et leurs transformations pour l'élaboration du produit, jusqu'à la fin de vie. L'ACV offre ainsi une vision holistique et multicritère du lien entre le système de production et l'environnement. Cette thèse porte sur l'adaptation de l'ACV au domaine de l'aquaculture et de la pêche en Tunisie. Son objectif est d'explorer les perspectives offertes par cette méthodologie afin de mieux caractériser le fonctionnement des systèmes de production de poissons et leur lien avec l'environnement. De plus, ce travail permet de fournir des recommandations stratégiques de gestion basées sur les résultats d'évaluations et de comparaisons pour améliorer les deux filières et assurer leurs durabilités.

Le premier volet de ce travail s'est focalisé sur l'adaptation de l'ACV au domaine aquacole. L'ACV a été appliqué à la totalité des fermes aquacoles tunisiennes, spécialisées dans l'élevage du bar (*Dicentrarchus labrax*) et de la daurade (*Sparus aurata*) dans des cages en mer. Six catégories d'impacts ont été incluses : acidification, eutrophisation, réchauffement climatique, occupation des surfaces terrestre, demande d'énergie cumulée et production primaire nette. Une ACV plus spécifique a été développée pour étudier l'impact environnemental lié à une seule ferme aquacole. Ensuite, des propositions d'améliorations ont été formulées, notamment pour la catégorie "sea-use" afin de mieux évaluer l'impact de l'occupation de l'espace marin. Pour cela, un modèle Meramod a été mis en place permettant de quantifier l'impact de la ferme aquacole sur les fonds marins. Ces études ont montré que les pratiques aquacoles et la production d'aliment de poisson sont les

contributeurs majeurs aux impacts environnementaux, ceci est expliqué par l'utilisation de farine et d'huile de poisson dans la fabrication de l'aliment.

Le deuxième volet de cette thèse a consisté à développer l'ACV au chalutage de fond dans le Golfe de Gabès, un haut lieu de la pêche en Tunisie. Dans un premier temps, l'ACV a permis d'évaluer les impacts environnementaux liés à la production d'une tonne de produits de la mer. Les catégories d'impacts étudiées sont l'épuisement des ressources abiotiques, l'acidification, l'eutrophisation, le réchauffement climatique, l'appauvrissement de la couche d'ozone, la formation d'oxydants photochimiques, la toxicité humaine, l'écotoxicité marine, l'écotoxicité terrestre, l'occupation des surfaces terrestre et la demande d'énergie cumulée. Ensuite, des indicateurs de qualité de l'écosystème (production primaire requise, indice trophique marin, indice des prédateurs supérieurs, niveau trophique des captures, etc.) ont été calculés pour compléter les résultats de l'ACV et prendre en compte la composante écologique dans l'analyse environnementale. Le modèle écosystémique Ecopath with Ecosim a permis de calculer ces indicateurs. Le module spatialisé Ecospace a été développé pour évaluer les conséquences environnementales et écosystémiques de différentes mesures de gestion simulées dans le Golfe de Gabès. Les résultats de cette analyse ont montré que les impacts sont proportionnels à la quantité de carburant nécessaire pour la production. En effet, l'amélioration de l'efficacité d'utilisation du carburant est un facteur clé pour améliorer le bilan environnemental de l'activité de pêche au chalut de fond.

Au final, les bilans environnementaux de l'aquaculture et du chalutage de fond en Tunisie ont été comparés. Une méta-analyse a été conduite pour comparer les impacts environnementaux en Tunisie à ceux d'autres écosystèmes et pour d'autres systèmes de production de produits de la mer. Les résultats révèlent que l'aquaculture a un potentiel d'eutrophisation plus élevé que la pêche. Par contre, la majorité des autres impacts étudiés sont plus accentués pour le chalutage de fond.

Ce travail a permis d'étudier les impacts environnementaux de l'activité aquacole et de la pêche au chalutage de fond en Tunisie. Les résultats de cette thèse ont un intérêt pour les gestionnaires en proposant des voies d'amélioration des deux secteurs afin de les placer dans un contexte de développement durable.

Mots clés: Analyse de Cycle de Vie (ACV), impact environnemental, aquaculture, pêche, chalutage de fond, modèle écosystémique, Tunisie, Golfe de Gabès.

Abstract

The main goal of ecology is to place human activities within a framework of sustainable development by enhancing their economic benefits, their social attractiveness and their environmental performances. Ecosystems that support fisheries and aquaculture are subject to several alterations of significant relevance to their functioning and to their abilities to provide goods and services. Therefore, the long-term sustainability of fishing is a major concern from an environmental and ecological viewpoint. Both activities carry risks of negative environmental impacts because of its close relation with the immediate environment. To better understand environmental impacts and ensure the sustainability of fishing and aquaculture, it is necessary to develop an integrative science-based approach to impact assessment. In this context, Life Cycle Assessment (LCA) has emerged as a robust method to estimate potential environmental impacts associated with seafood production throughout the supply chain. It allows the assessment of environmental impacts, at a global scale, taking into account all stages of a product's life, "from cradle to grave", from raw-material extraction to phases of construction, use, and disposal or recycling. This thesis focuses on the adaptation of LCA to demersal trawling and aquaculture in Tunisia. The objective of this work is to explore how LCA improves the environmental evaluation of seafood production systems and how it helps to better understand their functioning and their links with the environment throughout the production stages. In addition, this work provides practical information and strategic recommendations based on assessment and comparison results to improve fishing and aquaculture sectors and ensure their sustainability.

This work is divided into three principal parts. First, Life Cycle Assessment (LCA) was applied to assess potential environmental impacts generated by production of 1 ton of European seabass (*Dicentrarchus labrax*) and gilthead seabream (*Sparus aurata*) on all sea-cage aquaculture farms in Tunisia. Six impact categories were included: acidification, eutrophication, global warming, land occupation, total cumulative energy demand and Net Primary Production Use (NPPuse). Then, a specific LCA was developed to assess the environmental performance of only one aquaculture farm. A refinement of "sea use" impact category was proposed to assess impacts of aquaculture on the area of sea required and

seabed degradation; for that, a MERAMOD model was developed to quantify the amount of organic matter deposit under the cages. Results revealed that rearing practices and fish feed were the greatest contributors to the impacts studied due to the production of fish meal and oil and the low efficiency of feed use, which generated large amounts of nitrogen and phosphorus emissions. Therefore, it is essential to optimize diet formulation and to follow better feeding strategies and farming practices to lower feed-conversion ratios and consequently improve the environmental performance of aquaculture farms.

In the second part of this thesis, LCA was applied to demersal trawlers in the Gulf of Gabes, considered as one of the most productive fishery areas in Tunisia. LCA was developed to assess the environmental performance landing 1 t of seafood with demersal trawlers. Impact categories included in the study were abiotic depletion potential, acidification potential, eutrophication potential, global warming potential, ozone depletion potential, photochemical oxidant formation potential, human toxicity potential, marine eco-toxicity potential, terrestrial eco-toxicity potential, land occupation potential, and total cumulative energy demand. Then, ecosystem quality indicators were determined using an ecosystem modeling tool, Ecopath with Ecosim (EwE), and were combined with LCA to increase the relevance of both tools' assessments when applied to fisheries. Ecospace, the spatial module of EwE, was used to simulate different management scenarios. Results showed that impact intensity was proportional to the amount of fuel consumed to land 1 t of seafood. LCA also revealed that fish production and fuel and lubricating oil production contributed most to environmental impacts. Thus, improvements should focus principally on improving the efficiency of fuel use.

Finally, environmental performances of aquaculture and demersal trawling in Tunisia were compared. A meta-analysis was developed to compare environmental impact in Tunisia with those in other seafood production systems worldwide. Results revealed that aquaculture had higher eutrophication potential than demersal trawling. However, the majority of other impact categories were higher for demersal trawling.

LCA is a valuable tool for assessing how to improve environmental sustainability of demersal trawling and aquaculture; it provides stakeholders with insights into the main operational issues that require improvement.

Keywords: Life Cycle Assessment (LCA), Environmental impact, marine aquaculture, fisheries, demersal trawling, Tunisia, Gulf of Gabes.

الملخص

يعتبر الصيد البحري وتربية الأحياء المائية ضمن الضغوطات التي لها تأثير سلبي مباشر على الأنظمة الإيكولوجية و على البيئة البحرية و مواردها. من اهم الأهداف الإيكولوجية حالياً هو تطوير الأنشطة البشرية ضمن إطار التنمية المستادمة، و ذلك لتحسين المردود الاقتصادي و التنمية الإجتماعية و الأداء البيئي.

بسبب الاحتياجات المتزايدة إلى الموارد البحرية أصبحت التأثيرات البيئية أكثر وضوحاً. توجد اليوم العديد من الطرق لتقييم هذه التأثيرات. "تقييم دورة الحياة" هي أحد الوسائل الأكثر إستعمالا في العالم لدراسة وتقييم التأثيرات البيئية الناجمة عن صنع منتج .تتميز هذه الوسيلة بقدرتها على دمج جميع مراحل حياة المنتوج بأكملها، "من المهد إلى اللحد"، أي إبتدائا من استخراج المواد الخام و استعمالها، مرورا بمرحلة الصنع و الإستهلاك، وصولا إلى نهاية حياة المنتوج، إدارة النفايات و إعادة الإستعمال. هذه الوسيلة توفر نظرة شاملة عن علاقة المنتوج بالبيئة و التأثيرات الناتجة عن صناعته . اعتمدنا خلال هذه الأطروحة إستعمال هذه الطريقة لتقييم إنتاج 1 طن من المنتوجات البحرية عن طريق الصيد البحري و تربية الأحياء المائية. الهدف الرئيسي هو تحديد الأفاق المتاحة من إستعمال "تقييم دورة الحياة" من أجل فهم و وصف خصائص علاقة إنتاج المنتوجات البحرية بالتأثيرات البيئية. قمنا كذلك خلال هذا العمل بإعطاء نصائح و توصيات من أجل تطوير القطاعين و ضمان تنميتهما المستدامة.

لقد تم تطبيق "تقييم دورة الحياة" لدراسة التأثيرات البيئية الناجمة عن مزارع تربية سمك القاروص و سمك الوراطة في الأقفاص العائمة بالبلاد التونسية. من أجل تقييم التأثيرات المتعددة، قمنا بإختيار ستة "فئات تأثير" التالية : التحمض، اتخام المياه بالمغذيات، الاحتباس الحراري، إستعمال الأراضي، إجمالي الطلب من الطاقة المتراكمة و صافي الإنتاج الأولي. ثم استعملنا نفس الطريقة لدراسة التأثيرات البيئية لمزرعة تربية أسماك واحدة ، وقمنا بتطوير فئة تأثير جديدة تأخذ بعين الاعتبار التأثيرات النجمة عن هذا القطاع على قاع البحر. أظهرت نتائج هذه الدراسة أن إستخدام علف الاسماك لتغذيتها يعتبر السبب الرئيسي وراء معظم فئات التأثير. يمكننا أن نستنتج أن التأثيرات البيئية ترتبط مباشرة بنسبة التحويل الغذائي وطريقة التغذية، و من أجل الحد من زيادة المغذيات من الضروري تغيير الممارسات الغذائية.

في المرحلة الثانية في هذا العمل، قمنا باستعمال" تقييم دورة الحياة" المرطبة بإنتاج 1 طن من المنتجات البحرية باستعمال الجر القاعي في خليج قابس. فئات التأثير المختارة هي: إستنفاذ الموارد الغير حية، التحمض، اتخام المياه بالمغذيات، الاحتباس الحراري، إستنفاذ طبقة الأوزون، تكوين والمؤكسدات الكيميائية الضوئية ، السمية البشرية، السمية الإيكولوجية البرية،السمية الإيكولوجية البحرية، إستعمال الأراضي و إجمالي الطلب من الطاقة المتراكمة. ثم قمنا بإستعمال النموذج الغذائي "Ecopath with Ecosim" لدراسة خصائص النظام الإيكولوجي لخليج قابس. استعملنا كذلك نموذج "Ecospace" لتقييم التأثيرات البيئية و الإيكولوجية من خلال تطبيق سيناريوهات مختلفة لإدارة المصائد. الاستنتاج الرئيسي الذي تخلص إليه الدراسة هو أن شدة التأثيرات البيئية مرطبة بشكل مباشر بكمية الوقود المستهلكة لإنتاج 1 طن من المنتجات البحرية. لذلك يتوجب تحسين فاعلية إستخدم الوقود من أجل تحسين الأداء البيئي للصيد بالجر القاعي. أخيراً، قمنا بمقارنة الأداء البيئي لتربية الأحياء المائية و الصيد البحري. ثم استعملنا طريقة "Méta-analyses" لمقارنة النتائج التي تحصلنا عليها بنتائج دراسات سابقة. يمكننا أن نستنتج أن تربية الأحياء المائية لها تأثير أكبر على اتخام المياه

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الكلمات الرئيسية: تقييم دورة الحياة، التأثيرات البيئية، تربية الأحياء المائية، الصيد البحري، الجر القاعي،نماذج الأنظمة الإيكولوجية، تونس، خليج قابس.

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Liste des abréviations

ACP : Analyse en Composantes Principales

ACV : Analyse de Cycle de Vie

ADP : Abiotic Depletion Potential

AE : Approche Écosystémique

AEA : Approche Écosystémique de l'Aquaculture

AEP : Approche Écosystémique des Pêches

AP : Acidification Potential

API : Apex predator indicator

C : Carbon

CBD : Convention Sur La Diversité Biologique

CF : Characterisation Factor

CFC : Chlorofluorocarbons

CHCP : Classification Hiérarchique Sur Composantes Principales

CMED : Commission Mondiale Sur l'Environnement Et Le Développement

CTA : Centre Technique De l'Aquaculture

CV : Coefficient Of Variation

CFC : Chlorofluorocarbons

DCB : Dichlorobenzene

DGPA : Direction Générale De La Pêche Et De l'Aquaculture

EEZ : Exclusive Economic Zone

EP : Eutrophication Potential

EwE : Ecopath with Ecosim

FAO : Food And Agriculture Organization

FCR : Feed-Conversion Ratio

FU : Functional Unit

GDP : Gross Domestic Product

GUI : Graphical Use Interface

GWP : Global Warming Potential

HCPC : Hierarchical Clustering On Principal Components

HTP : Human Toxicity Potential

ICV : Inventaire De Cycle De Vie

ISO : Organisation Internationale De Normalisation

LCA : Life Cycle Assessment

LCI : Life Cycle Inventory

LOP : Land Occupation Potential

METP : Marine Eco-Toxicity Potential

MPA : Marine Protected Areas

MTI : Mean trophic index

N : Nitrogen

NPPuse : Net Primary Production Use

ODP : Ozone Depletion Potential

P : Phosphorous

PC : Principal Component

PCA : Principal Component Analysis

PNUE : Programme Des Nations Unies Pour L'environnement

POFP : Photochemical Oxidant Formation Potential

PPR : Primary Production Required

PPR : Production Primaire Requise

SETAC : Society For Environmental Toxicology And Chemistry

TBL : Triple Bottom Line

TE : Transfer effciency

TLc : trophic level of the catch

TCED : Total Cumulative Energy Demand

TETP : Terrestrial Eco-Toxicity Potential

ThOD : Theoretical Oxygen Demand

UF : Unité Fonctionnelle

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Introduction générale

1. Pêche et aquaculture : à la recherche d'un développement durable au service de la sécurité alimentaire mondiale

En 1987, le rapport Brundtland rédigé par la Commission mondiale sur l'Environnement et le Développement (CMED), mise en place par les Nations Unies, définit le développement durable comme suit : « un mode de développement répondant aux besoins des générations présentes sans compromettre la capacité des générations futures à répondre à leurs propres besoins » (Brundtland, 1987). La durabilité est généralement décrite selon la Triple Bottom Line (TBL) à laquelle sont associés les 3 P : « Profit », « People » et « Planet ». Ce concept des 3 P été mis en place par Elkington en 1994, qui a essayé d'élargir les stratégies d'une méthode de comptabilité purement économique (« profit ») pour prendre en compte les perspectives sociales (« people ») et environnementales (« planet ») (Elkington, 1994). Le développement durable doit assurer à la fois :

- L'efficacité économique : assurer une gestion saine et durable, sans préjudice pour l'environnement, il s'agit de trouver un juste milieu entre profit et gestion environnementale. L'économie est un moyen du développement durable.
- L'équité sociale : satisfaire les besoins essentiels de l'humanité et réduire les inégalités sociales tout en respectant les cultures. Le social est un objectif du développement durable.
- La responsabilité environnementale : maintenir l'équilibre écologique sur le long terme en préservant les ressources naturelles et en limitant des impacts environnementaux. Le respect de l'environnement est une condition du développement durable.

Le Comité de la Sécurité alimentaire mondiale définit la sécurité alimentaire comme : «(...) lorsque tous les êtres humains ont, à tout moment, la possibilité physique, sociale et économique de se procurer une nourriture suffisante, saine et nutritive leur permettant de satisfaire leurs besoins et préférences alimentaires pour mener une vie saine et active » (Comité de la Sécurité Alimentaire Mondiale, 2012).

La pêche et l'aquaculture ont une importante contribution à la sécurité alimentaire et la nutrition mondiale. Avec l'augmentation de la population mondiale, qui devrait atteindre 9,7 milliards de personnes en 2050, plusieurs rapports récents ont mis en avant la contribution considérable que les ressources marines peuvent apporter à la sécurité alimentaire mondiale (Godfray et al., 2010; HLPE, 2014). Les produits de la mer, d'aquaculture ou de capture, constituent la principale source de protéines et une source capitale de moyens d'existence et de revenus dans de nombreux pays en développement.

La demande mondiale de produits de la mer destinés à la consommation humaine a augmenté avec un rythme supérieur à 3,5% de croissance annuelle entre 1960 et 2014. Au cours de cette période, la consommation annuelle de produits de la mer par habitant a doublé, elle est passée de 10 à 20 kg par habitant (FAO, 2016). Cette augmentation permet à la population mondiale d'avoir un meilleur régime alimentaire, plus diversifié et plus nutritif. Le poisson est une source riche en protéines de grande qualité, il représentait 17% des apports en protéines animales de la population mondiale en 2013. En plus de sa richesse protéique, le poisson peut avoir des effets nutritionnels positifs. Il fournit des acides gras essentiels (oméga 3), des vitamines (D, A et B) et des minéraux (calcium, fer, etc.). Avec ses propriétés nutritionnelles, le poisson peut être valorisé pour rééquilibrer les régimes alimentaires et lutter contre l'obésité en se substituant à d'autres aliments (FAO, 2016). La consommation de poissons est influencée par la mondialisation des systèmes alimentaires et par les progrès technologiques et les innovations dans la transformation, distribution, transport et commercialisation, ce qui permet de réduire les coûts en offrant plus de choix (FAO, 2016). La pêche et l'aquaculture représentent une importante source d'emplois et de moyens d'existence pour la population mondiale. Les estimations indiquent qu'environ 820 millions de personnes (travailleurs et leurs familles) sont totalement ou partiellement tributaires de la pêche et de l'aquaculture (et des activités connexes) pour s'assurer un revenu économique (Allison et al., 2013). Les secteurs de la pêche et de l'aquaculture sont une importante source d'emplois et de revenu pour 56,6 millions de personnes (FAO, 2016).

À partir des années 1950, une augmentation continue de la production de produits de la mer de capture a été observée pour passer de 18 millions de tonnes à 78 millions de tonnes en 1988 (Figure 1). La production s'est ensuite stabilisée, avec quelques faibles fluctuations (FAO, 2016).

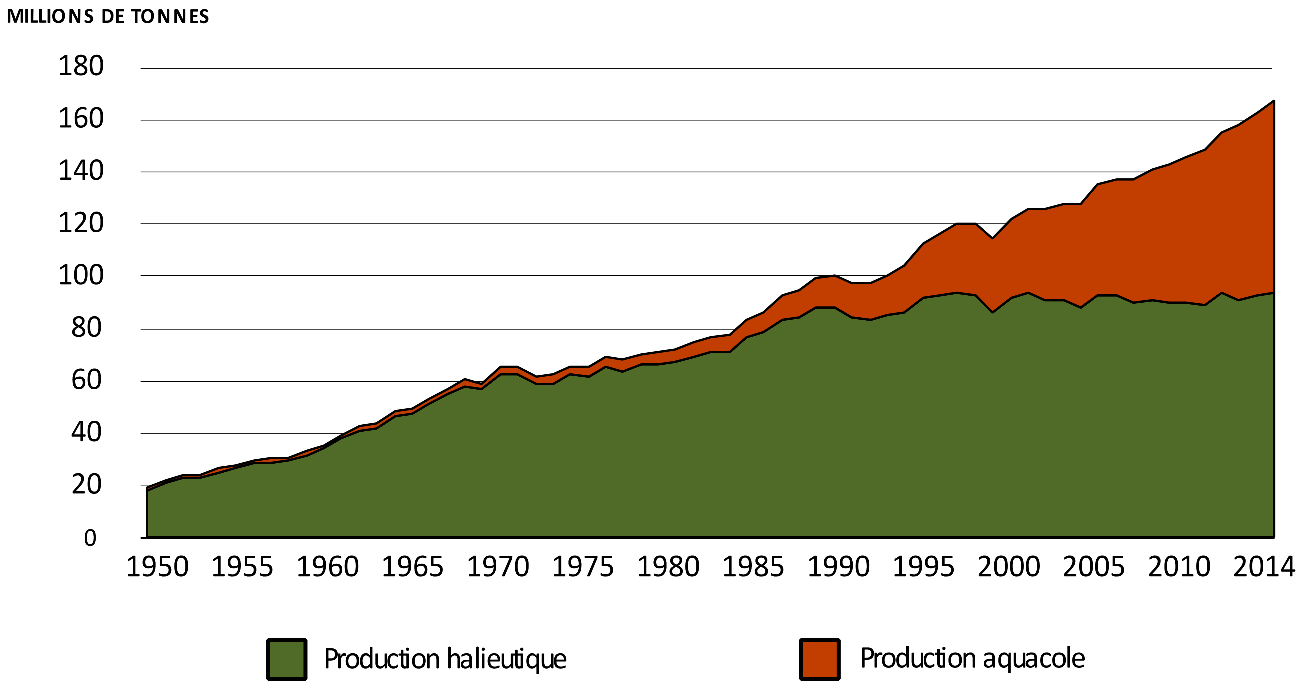


Figure 1 : Évolution de la production halieutique et aquacole mondiales entre 1950 et 2014 (FAO, 2016).

La production de poissons est passée de la capture d'organismes sauvages en milieu naturel à l'élevage d'un nombre croissant d'espèces (Naylor et al., 2000). La pêche est le prélèvement des ressources vivantes aquatiques dans le milieu marin (Christensen et al., 2003). Depuis les années 1980, la production de la pêche est relativement stable. La part de l'aquaculture dans l'offre de poisson est passée de seulement 7% en 1974 à 44% en 2014. La contribution du secteur aquacole à l'approvisionnement en poisson destiné à la consommation humaine a dépassé celle du secteur de la pêche en 2014 (FAO, 2016). La part de l'aquaculture dans la consommation humaine des produits de la mer est passée de seulement 0,8 kg par habitant en 1974 à 10,2 kg par habitant en 2014, alors que celle de la pêche est égale à 9,9 kg par habitant en 2014.

L'aquaculture est par définition la production d’animaux ou de végétaux en milieu aquatique. La production des produits de l'aquaculture s'élève à 73,8 millions de tonnes en 2014 (FAO, 2016)(Tableau 1). La production aquacole a augmenté avec un taux annuel de 5,8% entre 2005 et 2014. Cette production comprenait principalement la culture de poissons, de mollusques, de crustacés et d'autres animaux aquatiques (amphibiens, reptiles et invertébrés aquatiques). Cette activité est présente sur tous les continents et couvre une diversité importante en termes d'espèces cultivées et de systèmes de production. Le nombre d'espèces aquatiques cultivées dans le monde est égal à 580 en 2014 (dont 362 sont des poissons). Pour 35 pays dans le monde, la production de poissons d'élevage est plus importante que celle de poissons sauvages (par pêche) (FAO, 2016).

Tableau 1 : La production mondiale de produits de la mer par pêche et aquaculture entre 2009 et 2014 (FAO, 2016)

	2009	2010	2011	2012	2013	2014
Production (millions de tonnes)						
Pêche	90,2	89,1	93,7	91,3	92,7	93,4
Aquaculture	55,7	59,0	61,8	66,5	70,3	73,8
Total	145,9	148,1	155,5	157,8	162,9	167,2
Utilisation (millions de tonnes)						
Consommation humaine	123,8	128,1	130,8	136,9	141,5	146,3
Usage non-alimentaire	22,0	20,0	24,7	20,9	21,4	20,9

2. La pêche et l'aquaculture face aux enjeux environnementaux

2.1. L'aquaculture : un secteur en plein développement

La croissance rapide de la production aquacole au niveau mondial avait comme objectif majeur de maximiser la productivité et les rendements économiques (FAO, 2016). À court terme, cette approche a donné des résultats satisfaisants par rapport à la production et au revenu économique. En revanche, les résultats se sont avérés défavorables à long terme sur le plan environnemental, social et économique (HLPE, 2014). Il est donc nécessaire de planifier et de développer l'aquaculture dans un souci d'équilibre entre les objectifs sociaux, économiques et environnementaux. Le fonctionnement des systèmes aquacoles repose en grande partie sur l'utilisation de ressources naturelles, d'où la relation étroite entre l'aquaculture et l'environnement aquatique. Le milieu aquatique représente à la fois la source de plusieurs éléments nécessaires au fonctionnement des systèmes aquacoles (site, oxygène, éléments minéraux et même aliments dans certains cas) et le récepteur des rejets chimiques et biologiques liés à l'élevage (Read and Fernandes, 2003). Les interactions entre cette activité et l'environnement sont nombreuses et toute activité aquacole peut avoir des impacts sur l'environnement.

Les impacts sur l'environnement générés par les rejets et les effluents issus des fermes aquacoles sont nombreux. Les rejets les plus importants sont essentiellement les fèces et les aliments non consommés par les poissons. Les rejets de matières particulaires peuvent sédimenter sur les fonds des mers ou des lacs (Apostolaki et al., 2007; Kutti et al., 2008) ou dans les cours d'eau en aval des systèmes aquacoles connectés aux rivières (Bardonnet et al., 2004). Les rejets métaboliques des fermes aquacoles représentent une source de perturbations pour l'écosystème aquatique récepteur (d'Orbcastel et al., 2009; Neofitou et al., 2010) et peuvent modifier les biocénoses des milieux aquatiques et les communautés benthiques (Karakassis, 2000). Les atteintes peuvent varier selon les niveaux des flux et selon la résilience de l'écosystème (capacité de charge ou capacité d'accueil), qui correspond à sa capacité à transformer les flux de matières sans compromettre son fonctionnement (Richardson and Qian, 1999). En outre, les rejets peuvent être riches en xénobiotiques (produits de traitement, antibiotiques, antiparasitaires, désinfectants, biocides, hormones, adjuvants alimentaires, etc). Ce type de pollution est peu documenté, mais quelques études ont démontré le danger relatif à l'utilisation des xénobiotiques et leurs effets sur les organismes marins et l'environnement (Cabello, 2006; Defoirdt et al., 2011; Lalumera et al., 2004).

Un autre danger sur le plan environnemental est la fuite de poisson d'élevage dans le milieu naturel. Les poissons qui s'échappent peuvent être une source de diffusion de parasites dans l'environnement pouvant présenter des risques pour les populations sauvages (exemple des copépodes parasites qui ont infecté les élevages de saumon Atlantique et qui ont ensuite contaminé les populations sauvages de salmonidés (Middlemas et al., 2013)). Les poissons d'élevage qui échappent des fermes aquacoles peuvent entrer en interaction avec les espèces locales, soit par prédation soit par compétition sur les ressources disponibles (Abrantes et al., 2011). Dans certains cas, les espèces invasives peuvent engendrer des modifications du milieu marin (destruction des habitats (herbiers, algues...), bioturbation, etc) et par conséquent perturber les populations autochtones (par exemple des perturbations de cycles biologiques). Une autre source d'inquiétude, est le croisement entre les individus domestiqués (qui peuvent être sélectionnées sur des critères zootechniques) et ceux de la population autochtone, ce qui résulte à une perte de variabilité génétique de la population naturelle (Theodorou and Couvet, 2004).

Les impacts engendrés par l'aquaculture ne se limitent pas aux rejets, mais incluent également l'utilisation des ressources naturelles. L'un des points les plus polémiques en aquaculture est l'utilisation des ressources d'origine halieutiques pour l'alimentation des poissons d'élevage. Plusieurs études ont souligné la nécessité pour l'aquaculture d'optimiser la formulation et la production d'aliments ainsi que les pratiques de gestion et de distribution d'aliments pour diminuer les pertes en aliments aquacoles (Hasan and New, 2013). Les ingrédients majeurs dans la production d'aliments pour poissons sont la farine et l'huile de poisson puisqu'ils représentent les ingrédients les plus nutritifs et digestes pour les poissons en élevage. Plus de 60% des farines de poisson et plus de 80% des huiles de poisson de la production globale sont destinées à l'utilisation en aquaculture (Tacon and Metian, 2008). Par contre, la production de farine et d'huile de poisson a diminué avec la stagnation de la production halieutique de pêche. L'un des enjeux majeurs de la filière aquacole est de réduire la proportion de farine et d'huile de poisson dans les aliments d'élevage et de les substituer par d'autres ingrédients. La recherche s'est donc orientée vers d'autres sources de protéines tout en cherchant à garder les qualités nutritionnelles et organoleptiques des poissons d'aquaculture (Dias et al., 2009).

2.2. La pêche : un secteur en pleine mutation

Avec l'amélioration des techniques de pêche et l'extension des zones de capture, une partie de cette demande est satisfaite par l'activité de pêche (HLPE, 2014). Ce secteur est en pleine mutation avec l'augmentation des puissances des navires, l'amélioration de la résistance des filets (fibres synthétiques), les progrès technologiques et d'amélioration des moyens de détection des ressources, les meilleures conditions de conservation et de transformation des produits de la mer, etc (Pauly et al., 2002). Au niveau environnemental, la pression exercée par la pêche est grandissante. L'impact le plus direct de la pêche est la réduction de l'abondance des espèces cibles (Costello et al., 2016). De plus, la pêche affecte les communautés de poissons à travers les modifications des structures de tailles et la composition en espèces. La proportion de stocks de poissons exploités à un niveau biologiquement durable à long terme (ou sous-exploités) a diminué de manière continue à l'échelle mondiale entre 1974 et 2013, elle a baissé de 90% en 1974 à 68,6% en 2013 (FAO, 2016) (Figure 2). Seulement 10,5% des stocks de poissons évalués en 2013 sont sous-exploités et 58,1% sont exploités au rendement maximal durable. Les autres 31,4% des stocks de poissons sont exploités à un niveau biologiquement non viable et dépassent leur capacité de régénération (FAO, 2016). La dégradation de l'état des stocks est due essentiellement à la surpêche (Daskalov et al., 2007; Layman et al., 2011). La surpêche est un problème mondial qui engendre des répercussions graves au niveau social, économique et environnemental. La surexploitation des ressources marine est liée à l'intensification de l'effort de pêche ce qui a conduit à une réduction de la biodiversité (Worm et al., 2006) et même à l'effondrement de certains stocks (par exemple, le stock de morue du Canada (*Gadus morhua*) (Bundy and Fanning, 2005). Ceci se produit lorsque les espèces ne sont plus en mesure de faire face à la pression intense de pêche et d'assurer le renouvellement de leurs populations. La pression de la pêche engendre également des effets négatifs sur la structure des réseaux trophiques par des interactions complexes entre les espèces. En effet, un changement de biomasse d'un groupe trophique entraine par le biais de la cascade trophique des modifications des biomasses des autres groupes.

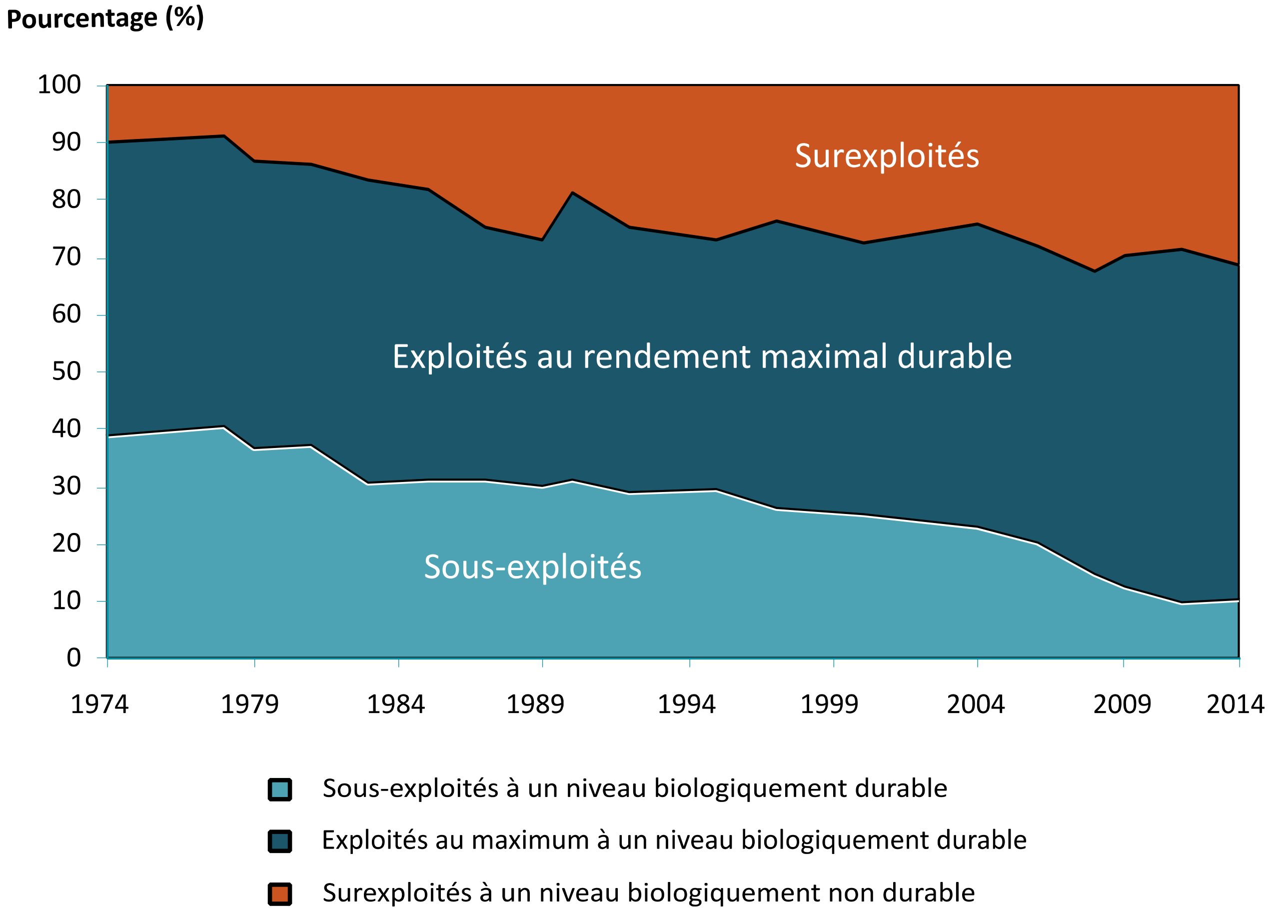


Figure 2 : Évolution de l'état des stocks de poissons dans le monde entre 1974 et 2014 (FAO, 2016).

Les conséquences de l'intensification de la pression de pêche vont au-delà du prélèvement de la ressource dans le milieu naturel (Kaiser et al., 2002). La pêche détruit en effet les habitats, modifie les substrats des écosystèmes exploités ainsi que la structure et le fonctionnement de ces derniers. Les engins de pêche qui raclent les fonds marins ont des conséquences graves sur les peuplements benthiques (Kaiser et al., 2006, 2002; Piet et al., 2000). Ces engins trainant affectent la structure des fonds marins (les éponges, les bryozoaires, les colonies de polychètes, les coraux profonds, etc). La dégradation de ces structures d'origine biogène peut engendrer une réduction de la diversité des habitats et par conséquent, une diminution de la diversité des populations de poissons qui utilisent ces structures comme habitat (Guyonnet et al., 2008; Moran and Stephenson, 2000; Wassenberg et al., 2002). Ces engins influencent également les propriétés physiques des fonds marins et des sédiments, augmentent la turbidité et modifient les processus d'échanges chimiques (McConnaughey et al., 2000).

Les prises accessoires ou accidentelles font partie des impacts les plus importants de l'activité de pêche. Il s'agit de l'ensemble des espèces qui ne sont pas ciblées par la pêcherie mais qui malgré tout sont capturées (Glass, 2000). Le volume des captures accessoires peut être plusieurs fois supérieur à celui des prises d'espèces cibles. L'ampleur exacte des prises accessoires et des rejets est difficile à estimer, étant donnée la variabilité importante selon les pêcheries. Les rejets et les prises accessoires sont estimés à environ 7,3 millions de tonnes par an (Kelleher, 2008). D'autres études estiment les rejets à 28,5 millions de tonnes par an (Davies et al., 2009). Les captures accessoires se composent principalement de poissons de petite taille et de faible valeur commerciale, mais dans certains cas, elles peuvent comprendre des juvéniles d'espèces de poissons de haute importance commerciale et/ou écologique, ainsi que des animaux vulnérables (tortues de mer, requins, raies, etc). En plus des poissons, mollusques et crustacés, les scientifiques estiment que plus que 653 000 mammifères marins sont victimes des prises involontaires et meurent emmêlés dans les filets de pêche (Read et al., 2006; US Comm'n on Ocean Policy, 2004). Les impacts de la pêche sont donc très variés et les conséquences de cette activité sont de plus en plus étudiées par les scientifiques, les économistes et les décideurs.

2.3. L'approche écosystémique des pêches et de l'aquaculture

La gestion durable de l'environnement est devenue une nécessité juridique avec l'adoption de la Convention sur la Diversité Biologique (CBD, 1992). Le développement de pêche et de l'aquaculture dans le monde engendre plusieurs impacts environnementaux qui doivent être prise en compte et diminués pour assurer la durabilité à long terme des deux secteurs. Pour aborder les enjeux environnementaux liés aux activités humaines, l'approche écosystémique (AE) est considère comme un outil pertinent dans le contexte de la pêche et de l'aquaculture. Cette approche permet une gestion holistique des écosystèmes pour favoriser l'utilisation durable et équitable de leurs ressources. L'AE se base sur les principes du développement durable et ne se limite donc pas à des considérations d'ordre écologiques mais inclut également des considérations économiques et sociales.

La notion d'approche écosystémique des pêches (AEP) est apparue dans le Code de conduite pour une pêche responsable, publié en 1995 par la FAO. La définition a été reprise lors de la consultation d'experts organisée en 2002 à Reykjavik, à l'initiative de la FAO et faisant suite à la Déclaration des chefs d'État de Reykjavik de 2001, sur la pêche responsable dans l'écosystème marin. L'AEP peut être définie comme : « l'approche qui a pour objet de planifier, de valoriser et de gérer les pêches, en tenant compte de la multiplicité des aspirations et des besoins sociaux actuels, et sans remettre en cause les avantages que les générations futures doivent pouvoir tirer de l'ensemble des biens et services issus des écosystèmes marins ». L'AEP doit être considérée comme une application des principes du développement durable au domaine de l'exploitation halieutique. L'application de l'AEP permet d'étudier les effets de la pêche, en prenant en considération les populations, les réseaux trophiques et les habitats des ressources halieutiques (Cury et al., 2008). Elle a pour but d'éviter la dégradation des écosystèmes et leurs structures et fonctionnements, tout en maintenant leur viabilité socio-économique à long terme. Le principe de l'AEP est de passer d'une situation où le rendement économique est relativement faible avec un impact environnemental important, à une situation où la rentabilité économique est meilleure avec un impact environnemental modéré assurant ainsi la durabilité du secteur (Gascuel, 2009).

L'aquaculture peut engendrer des impacts importants sur l'environnement ainsi que des incidences sociales négatives. C'est pourquoi la FAO a lancé un atelier "Construire une Approche Écosystémique de l'Aquaculture" pour définir les bases et les directives nécessaires pour le développement durable du secteur aquacole (Soto et al., 2011). L'approche écosystémique de l'aquaculture (AEA) est définie comme : « une stratégie pour l'intégration de l'activité au sein de l'écosystème élargi de telle sorte qu'il favorise le développement durable, l'équité et la résilience des systèmes socio-écologiques interdépendants ». L'AEA s'appuie sur les principes de l'AEP. L'objectif principal est de mettre en place un secteur d'aquaculture durable économiquement, socialement et environnementalement. L'AEA vise aussi à changer l'attitude publique et la perception de l'aquaculture et des produits aquacoles (Soto et al., 2011). Cette approche se base sur le principe que le développement de l'aquaculture et sa gestion devraient prendre en compte les fonctions et services écosystémiques et systématiquement favoriser la durabilité de l'aquaculture. Pour cela, il est important d'adapter les pratiques aquacoles selon les limites des écosystèmes et leurs capacités d'assimilation. Pour appliquer l'AEA, l'aquaculture devrait avoir pour objectif d'améliorer le bien-être humain et l'équité pour toutes les parties concernées. Il faut que l'activité aquacole offre des possibilités équitables pour le développement et le partage équitable de ses avantages d'une manière à assurer la sécurité alimentaire (quantité d'aliments) et la sûreté alimentaire (la qualité d'aliments) à tous les groupes dans la société (Neori et al., 2007; Soto et al., 2008).

3. Aperçu sur l'exploitation des produits de la mer en Tunisie

La Tunisie occupe une place centrale dans la Méditerranée (Figure 3). Avec ses deux façades maritimes longeant 1 350 km et un domaine maritime national de 80 000 km^2, la Tunisie a toujours été considérée comme un pays où le secteur de la pêche et de l'aquaculture jouent un rôle important sur le plan aussi bien socio-économique qu'alimentaire. Une augmentation de la production des produits de la mer de 11%, soit 11 909 tonnes, entre 2004 et 2013, a permis d'atteindre une production totale de 122 000 tonnes (Direction Générale de la Pêche et de l'Aquaculture, (DGPA, 2014)).

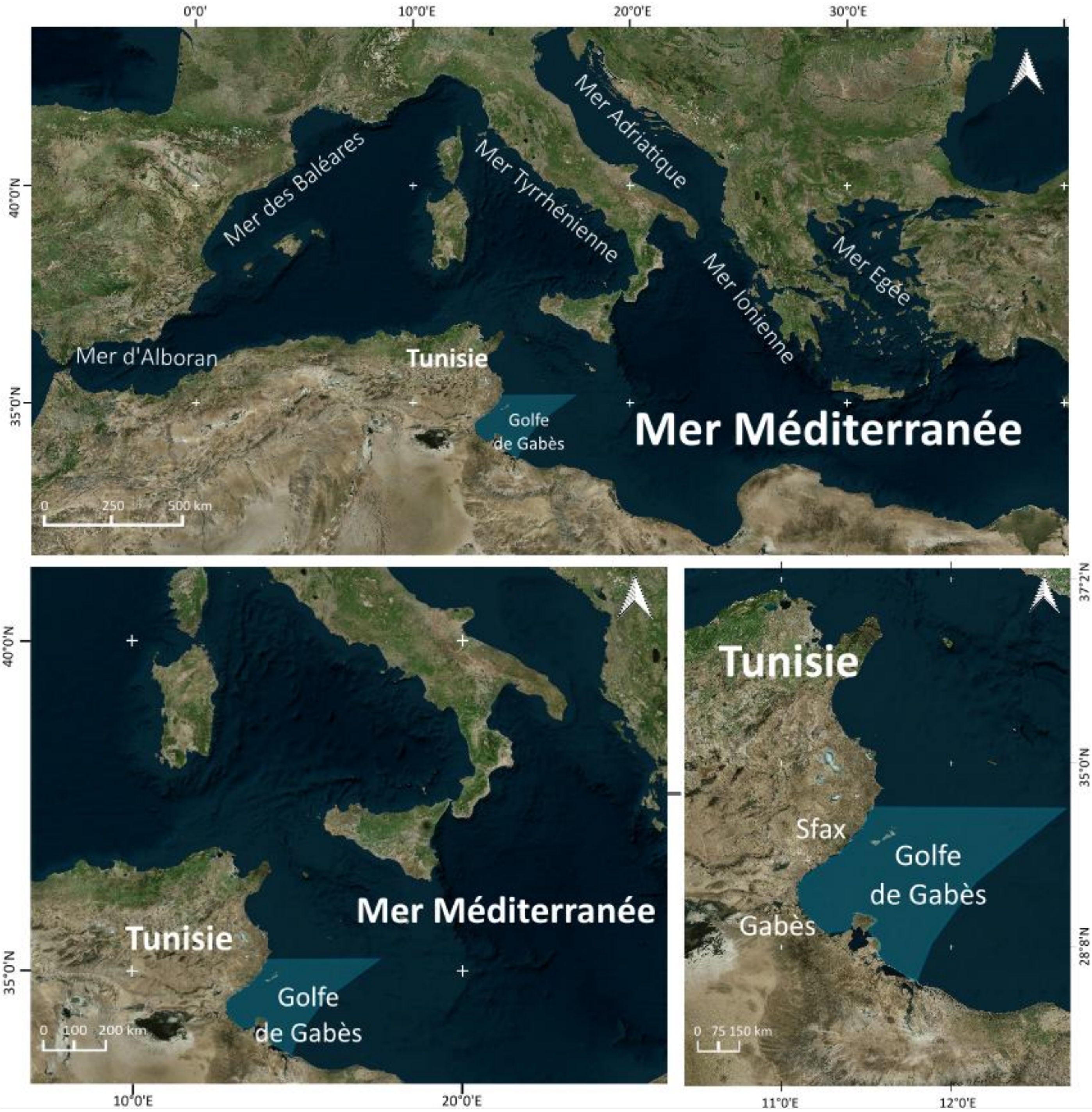


Figure 3 : Situation géographique de la Tunisie et du golfe de Gabès en Méditerranée.

3.1. L'aquaculture en Tunisie

L'aquaculture en Tunisie est considérée comme une activité ancienne qui remonte à l'époque romaine. Les premières traces d'aménagement extensif en eau marine se manifestent par les vestiges d'une exploitation d'élevage de mulets comme l'attestent les mosaïques du Musée du Bardo. L'une des premières expériences en aquaculture remonte aux années 1960 avec la conchyliculture (mytiliculture) dans la lagune de Bizerte pour l'élevage de la moule méditerranéenne (*Mytilus galloprovincialis*) et l'huître creuse (*Crassostrea gigas*). Cette expérience était suivie par l'installation d'une écloserie marine à Ghar el Melh, dans le nord du pays, en 1973 (CTA, 2016).

Dans les années 1990, un plan directeur de l'aquaculture a était mis en place et une pisciculture continentale s'est développée. En 2003, quatre projets d'engraissement du thon rouge (*Thunnus thynnus*) ont été créés. Le thon capturé en mer et destiné à l'engraissement est transféré vivant dans des cages flottantes en pleine mer, où il est engraissé en captivité pendant quelques mois. Ce secteur est soumis aux quotas fixés par la Commission Internationale de la Conservation des Thonidés de l'Atlantique (ICCAT) (CTA, 2016).

L'aquaculture en Tunisie assure une production qui dépasse 10 000 tonnes en 2015 ce qui représente 11% de la production halieutique totale tunisienne. Ce secteur offre plus d'un millier de postes d'emplois directs et permanents (DGPA, 2015). À l'échelle de la Méditerranée, l'aquaculture en Tunisie est considérée comme une petite industrie avec un important potentiel de croissance. Elle était classée 8^{éme} en terme de production en 2013 et contribue à raison de 1% à la production aquacole totale de Méditerranée (FAO, 2016). L'aquaculture en Tunisie est de quatre types (i) la pisciculture marine, (ii) l'engraissement du thon, (iii) la pisciculture continentale et (iv) la conchyliculture (DGPA, 2014). La pisciculture marine est le secteur de l'aquaculture qui attire le plus les investisseurs tunisiens, ce qui est traduit par une croissance rapide du nombre de projets aquacoles dans des cages flottantes. Le nombre de sociétés piscicoles est passé de seulement 4 en 2009 à 25 en 2014 (DGPA, 2014). Les espèces les plus importantes du point de vue valeur en élevage sont essentiellement le bar (*Dicentrarchus labrax*) et la dorade royale (*Sparus aurata*). La production de la pisciculture marine est passée de 985 tonnes en 2003 à presque 10 000 tonnes en 2014. Cependant, la production aquacole des trois autres types d'aquaculture est restée stable. La production annuelle d'engraissement du thon est voisine de 480 tonnes de 2005 à 2014, celle de la pisciculture continentale est proche de 1 040 depuis 2005, il s'agit de l'élevage de poissons (principalement de la carpe (*Cyprinus carpio*), du tilapia (*Oreochromis niloticus*), les mulets (*Mugil cephalus* et *Liza ramada*) et le sandre (*Stizostedion lucioperca*)) dans les retenues de barrages. Enfin, la production de la conchyliculture est passée de 121 tonnes en 2005 à 162 tonnes en 2014, cette production se limite à l'élevage des moules et des huîtres (DGPA, 2014).

3.2. La pêche en Tunisie

La pêche est considérée comme une activité économique importante en Tunisie. Elle représente 8 % de la production agricole nationale (DGPA, 2014). La Tunisie dispose de plus de 40 ports de pêche maritime. Historiquement, la pêche industrielle en Tunisie était concentrée dans le nord du pays. Au début du siècle précédent, la pêche au chalut et à la senne était principalement pratiquée par les français et les italiens (De Fages and Ponzevera, 1903); en revanche, la pêche côtière était pratiquée par les tunisiens dans le golfe de Gabès (Romdhane, 1998). À partir de 1960, il y a eu un déplacement de l'activité de pêche au chalut et à la senne des côtes nord du pays vers les zones côtières est et dans le Golfe de Gabès.

Grâce à ses caractéristiques océanographiques et géomorphologiques particulières, le Golfe de Gabès représente la zone la plus productive en termes de production primaire malgré les conditions oligotrophiques de la Méditerranée (Papaconstantinou and Farrugio, 2000). Il se caractérise par de larges herbiers de posidonie (*Posidonia oceanica*) (Ben Mustapha and Afli, 2007). Cet habitat offre une nurserie pour les juvéniles et une zone de frayère et de refuge pour plusieurs espèces marines (Hattour et al., 2013). Le Golfe abrite 247 espèces de poissons parmi 327 espèces recensées en Tunisie (Bradai et al., 2004).

À partir des années 1970, le Golfe de Gabès a connu une intensification de l'effort de pêche et une croissance importante du nombre d'unités de pêche. Le chalutage benthique est l'activité prédominante dans le Golfe de Gabès ; le nombre de chalutiers benthiques est passé de 72 unités à 221 unités en 1988, ceci s'est traduit par un pic de production halieutique (66 000 tonnes en 1988) (DGPA, 2014) (Figure 4). Cette intensification a menacé la durabilité de la pêche (Ben Meriem et al., 2005) et elle a engendré une baisse des ressources marines à partir des années 1990, suivie par le début de la surexploitation des stocks et la prise de conscience de l'importance de la durabilité de la pêche. Le rendement horaire moyen des chalutiers a diminué de 75 $kg.h^{-1}$ en 1971 à seulement 37 $kg.h^{-1}$ en 2001 (Gharbi and Zaarah, 2001; Hattour, 1991). Le chalutage benthique dans le golfe de Gabès est peu sélectif et les rejets et prises accessoires sont nombreux. Les rejets dépassent souvent

50%, leur rendement horaire est estimé à 73 $kg.h^{-1}$ (Jarboui et al., 2005). De plus, plusieurs stocks ont été diagnostiqués comme étant surexploités, notamment les rougets (*Mullus barbatus*, *Mullus surmuletus*) ou le pageot commun (*Pagellus erythrinus*) (Ben Meriem et al., 1994a; Gharbi et al., 2004; Jarboui et al., 1998).

Les pêcheries du Golfe de Gabès ont pour caractéristiques d'être multi-espèces, multi-engins ciblant des espèces démersales et pélagiques en utilisant des chaluts, filets droit, sennes, palangres etc. Le chalutage benthique et la pêche côtière sont les deux activités principales dans le golfe en terme de flottille et de valeur des débarquements (Mosbah et al., 2013). À partir des années 2000, le nombre des barques côtières non motorisées a diminué pour passer de 5 878 en 1995 à 3 411 en 2005. Le nombre des chalutiers benthiques est resté relativement stable (autour de 260 chalutiers) (DGPA, 2014). Entre 2000 et 2010, la production totale annuelle au niveau du Golfe de Gabès a dépassé les 40 000 tonnes correspondant à 40% de la production nationale annuelle. En 2014, la production totale du Golfe de Gabès a dépassé 46 100 tonnes, mais sa part dans la production nationale a diminué à 36% (DGPA, 2015).

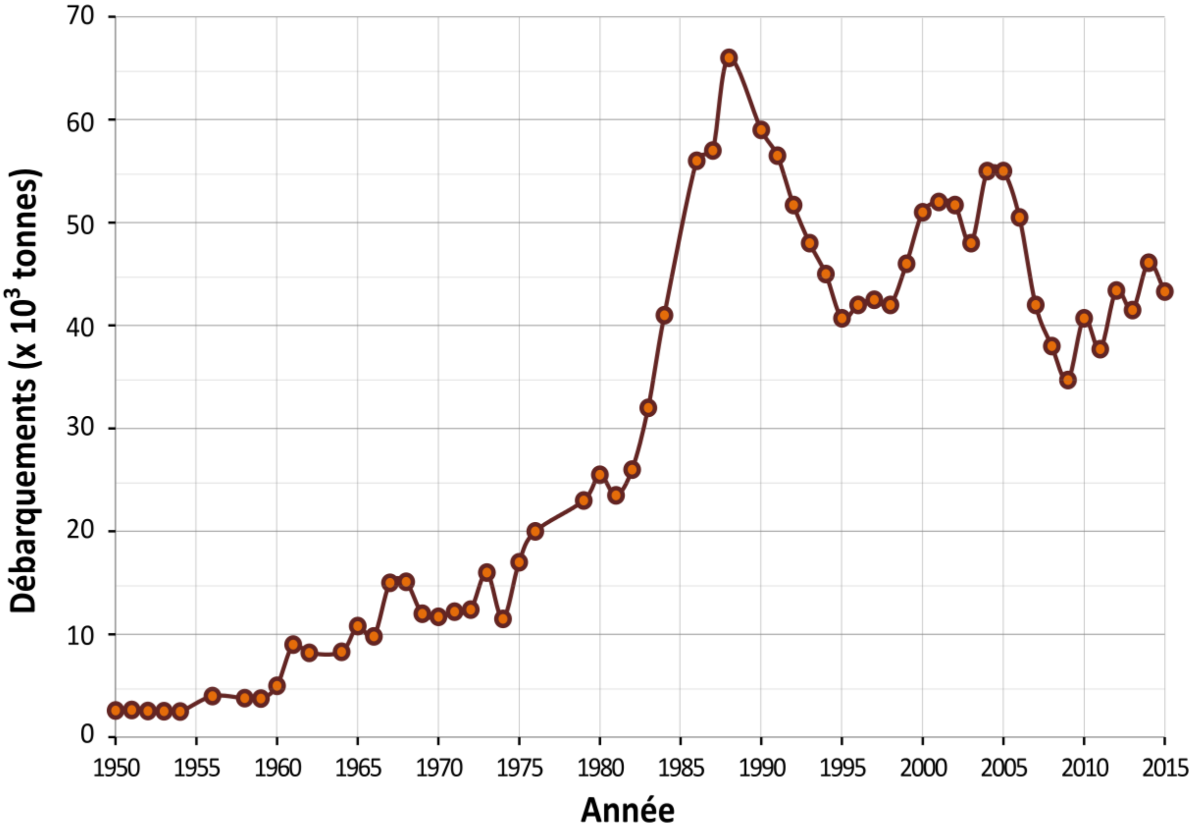


Figure 4 : Evolution de la production totale dans le golfe de Gabès entre 1950 et 2015 (données des rapports statistiques de la Direction Générale de la Pêche et de l'Aquaculture et de l'Institut National des Statistiques) (Halouani et al., 2015a).

Le golfe de Gabès se situe dans le bassin oriental de la Méditerranée et s'étend de Ras Kapoudia au 35ème parallèle jusqu'à la frontière tuniso-libyenne couvrant une superficie totale d'environ 35 900 km^2 (Figure 3). Bien qu'il soit considéré comme l'une des zones de pêche les plus productives en Tunisie, le Golfe de Gabès est considéré comme un écosystème archétypal puisqu'il est le siège de plusieurs forçages recensés à l'échelle régionale de la Méditerranée (Ben Rais Lasram et al., 2015a). Il subit une pollution chimique causée par les rejets du phosphogypse de l'usine de Ghannouch ainsi qu'une forte accumulation des métaux lourds dans les sédiments (Rabaoui et al., 2013). Le Golfe de Gabès est sujet à une augmentation de la température causée par le changement climatique, une augmentation moyenne de la température de l'ordre de 0,042°C par an a été observée entre 1985 et 2008 (Skliris et al., 2011). Ces menaces ont causé des modifications des réseaux trophiques (Ayadi et al., 2015) et des patrons de distribution des espèces méditerranéennes en favorisant l'introduction de espèces exotiques (Ben Rais Lasram, 2009). Les espèces nouvellement introduites peuvent devenir abondantes dans l'écosystème, à l'exemple de la crevette blanche (*Metapenaeus monoceros*) (Ben Abdallah et al., 2003), le crabe bleu (*Portunus segnis*) (Rabaoui et al., 2015) et les poissons (*Lagocephalus sceleratus* (Jribi et al., 2012) et *Seriola fasciata* (Bradai et al., 2004)).

4. Objectif de la thèse

Aujourd'hui, la gestion durable de l'environnement est considérée comme une nécessité juridique et une condition indispensable pour le développement des activités humaines. Avec l'adhésion de la Tunisie à l'Organisation Mondiale du Commerce et l'accord d'association et de libre-échange avec l'Union Européenne, l'économie tunisienne doit faire face à plusieurs difficultés pour être en concurrence avec l'industrie des autres pays. Le secteur de la pêche et de l'aquaculture nécessite une attention particulière puisqu'il occupe une place non négligeable dans l'économie tunisienne.

À la croisée entre les enjeux forts de l'alimentation et la gestion durable des ressources marines, il devient de plus en plus important de développer des outils pour évaluer les performances environnementales de la pêche et de l'aquaculture, vu les nombreuses interactions qui existent entre ces activités et l'environnement. Ces outils doivent permettre de mieux comprendre le fonctionnement des systèmes de production de poissons et de proposer des moyens d'amélioration du secteur pour assurer sa durabilité à long terme. Pour cela, l'Analyse des Cycles de Vie (ACV) émerge comme un outil pertinent pour l'analyse environnementale. Il s'agit d'une méthode normalisée prenant en considération l'ensemble des étapes de la vie d'un produit. L'ACV se veut exhaustive et offre une vision holistique et multicritère des interactions entre le système de production et l'environnement.

L'objectif principal de cette thèse est d'adapter et mettre en œuvre une ACV de l'activité de pêche et de l'aquaculture. Plus qu'un travail méthodologique, il s'agit de démontrer la pertinence de l'ACV pour éclairer le fonctionnement des systèmes de production de poissons et leur lien avec l'environnement. Des améliorations du cadre méthodologique de l'ACV pour l'adapter aux systèmes de production de poissons seront proposées. Celles-ci doivent notamment permettre de prendre en compte plusieurs autres composantes jugées importantes pour le développement durable des secteurs de la pêche et de l'aquaculture. Enfin, ce travail permettra de répondre aux questions de recherches suivantes:

- **Quels sont les impacts environnementaux de la production de poissons par aquaculture et par pêche en Tunisie ?**
- **L'ACV permet-elle de mieux comprendre le fonctionnement des systèmes de production de poissons et d'identifier les points focaux à améliorer pour avoir un bilan environnemental meilleur ?**
- **L'ACV est-elle en mesure de prendre en considération les spécificités de l'aquaculture et de la pêche pour évaluer leurs impacts environnementaux ?**
- **Aquaculture ou pêche en Tunisie ? Quelle activité est dotée d'un meilleur bilan environnemental ?**

Cette thèse s'articule autour de trois principaux chapitres en dehors du chapitre introductif et du chapitre de conclusions et perspectives. Le manuscrit est construit sur cinq articles scientifiques, dont trois sont publiés et deux sont soumis dans des revues scientifiques à comité de lecture. Le chapitre introductif présente le contexte général du travail et décrit les enjeux environnementaux de la pêche et de l'aquaculture.

Le premier chapitre détaille le principe et le cadre conceptuel de l'ACV.

Le deuxième chapitre est consacré à la partie aquaculture de la thèse. Il est basé sur deux articles publiés : « Rearing performances and environmental assessment of sea cage farming in Tunisia using life cycle assessment (LCA) combined with PCA and HCPC » (Abdou et al., 2017a) dans « the International Journal of Life Cycle Assessment » et « Environmental assessment of seabass (*Dicentrarchus labrax*) and seabream (*Sparus aurata*) farming from a life cycle perspective: A case study of a Tunisian aquaculture farm » (Abdou et al., 2017b) dans « Aquaculture ». Ces articles montrent comment l'ACV permet de transformer et synthétiser les informations techniques des fermes aquacoles en Tunisie pour établir un bilan environnemental de l'activité. Le but est d'évaluer les impacts environnementaux de l'élevage du bar et de la daurade dans des cages en mer en Tunisie et de proposer des moyens d'amélioration du secteur. Dans la première partie de ce chapitre, une nouvelle méthode de catégorisation des fermes d'aquaculture est proposée en se basant sur la méthode d'Analyse en Composantes Principale (ACP), ce qui permet de prendre en compte plusieurs caractéristiques (nombre de cages, tilles des cages, profondeur sous les cages, le ratio de conversion alimentaire, etc) au lieu de se baser seulement sur un seul critère de classification.

La deuxième partie du chapitre 2 consiste à l'adaptation et l'utilisation du cadre méthodologique de l'ACV à une seule ferme aquacole et à proposer des améliorations de la catégorie d'impact "sea-use", afin de prendre en compte les spécificités de l'aquaculture et mieux évaluer l'impact de l'occupation de l'espace marin. Pour cela, un modèle Meramod a été mis en place permettant de quantifier l'impact de la ferme aquacole sur les fonds marins.

Le troisième chapitre s'intéresse à la pêche au chalutage benthique dans le Golfe de Gabès. Il s'articule autour de deux articles scientifiques : « Environmental life cycle assessment of seafood production: A case study of trawler catches in Tunisia » (Abdou et al., 2018) publié dans « Science of the Total Environment » et « Combining ecosystem indicators and life cycle assessment for environmental assessment of demersal trawling in Tunisia » soumis dans « Science of the Total Environment ». Dans le premier article, l'ACV a été appliquée aux chalutiers benthiques ce qui a permis d'évaluer les impacts environnementaux liés à la production de poissons. En réponse au manque méthodologique de l'ACV pour la prise en compte des impacts biologiques de la pêche sur les espèces et les écosystèmes marins, le deuxième article de ce chapitre dresse le cadre méthodologique pour inclure de nouveaux indicateurs de qualité de l'écosystème pour compléter les résultats de l'ACV et prendre en compte la composante écologique dans l'analyse environnementale. Pour calculer ces indicateurs, le modèle écosystémique Ecopath with Ecosim a été utilisé. Ensuite, le module spatialisé Ecospace a été mis en œuvre pour évaluer les conséquences environnementales et écosystémiques de différentes mesures de gestion (aires marines protégées, périodes de repos biologique, diminution du nombre de chalutiers benthiques) simulées dans le Golfe de Gabès.

Le chapitre 4 est une analyse comparative des bilans environnementaux de l'aquaculture et de la pêche au chalutage de fond en Tunisie. En plus de la comparaison, une méta-analyse a été conduite pour comparer les impacts environnementaux en Tunisie à ceux d'autres écosystèmes et pour d'autres systèmes de production de produits de la mer. Pour cela, une revue exhaustive des ACV de produits de la mer a été réalisée. Ce chapitre fait l'objet d'un article scientifique : « Comparing environmental impacts of aquaculture and demersal trawling activity using life cycle assessment (LCA) framework and meta-analysis » prêt à être soumis dans « the Journal of Cleaner Production ».

Enfin, une discussion sur les apports de l'ACV pour l'évaluation environnementale de l'aquaculture et de la pêche et sur les limites de la méthode, une conclusion reprenant les points saillants et les perspectives de ce travail sont présentées dans le chapitre conclusion et perspectives.

Chapitre 1

L'analyse du Cycle de Vie (ACV), une approche holistique d'évaluation environnementale

1.1. Historique et définition de l'ACV

Face à l'épuisement des ressources et à la capacité réduite de l'environnement à soutenir les effets de l'activité humaine, il est devenu important de porter plus d'intérêt aux problématiques environnementales afin de limiter les impacts négatifs de ces activités et d’atténuer leurs répercussions sur les ressources et les écosystèmes. Plusieurs méthodes d'évaluation environnementale ont donc vu le jour. L'analyse de différentes méthodes d'analyse environnementale en agriculture a montré que les méthodes proposant une large gamme d'indicateurs (allant des échelles locales au globales) sont les méthodes les plus pertinentes et complètes (Van Der Werf and Petit, 2002). L'Analyse de Cycle de Vie (Life Cycle Assessment (LCA)) répond à ces critères. Cette méthode, qui fait partie des "approches orientées produit", a d'abord été conçue à la fin des années 1960 pour associer la consommation d'énergie et l'utilisation de matériaux bruts avec la production d'un produit. En revanche, l'interprétation des analyses conduites durant cette période n'était pas une tâche facile. Cette situation résulte du manque d'harmonisation et de la non-standardisation entre les méthodes appliquées. La SETAC (Society for Environmental Toxicology And Chemistry) a mis en place une première définition du cadre méthodologique de l'ACV en 1991 (Fava et al., 1991). En plus de la SETAC, cette méthode est supportée par l'Organisation Internationale de Normalisation (ISO) et le Programme des Nations Unies pour l’environnement (PNUE). En 1997, quatre normes ont été établies (ISO 14040, 14041, 14042, 14043) décrivant respectivement le cadre méthodologique de l'ACV, les étapes de l'inventaire, l'évaluation des impacts et l'interprétation des résultats. En 2006, ces normes ont été fusionnées en deux normes ISO 14040 (ISO, 2006a) et 14044 (ISO, 2006b) qui définissent les principes généraux de l'ACV et le contenu technique destiné aux praticiens de l'ACV.

L'ACV permet d'évaluer l'ensemble des impacts environnementaux potentiels d'un produit, d'un procédé ou d'un service (Figure 1.1), en prenant en considération l'intégralité de son cycle de vie, «*du berceau à la tombe*» (« from cradle to grave »), c'est à dire, depuis la source (extraction de matières premières) jusqu'à la fin de vie (traitement ou élimination des déchets, recyclage) (Guinée et al., 2002). L'ACV est une approche holistique multi-étapes puisqu'elle prend en compte la totalité des étapes associées à la fonction étudiée, et multi-critères puisqu'elle permet d'évaluer plusieurs catégories d'impacts environnementaux relatifs à différents compartiments (air, eau, sol, ressources naturelles, etc.) et allant des impacts locaux (eutrophisation, acidification, toxicité etc.) aux globaux (réchauffement climatique, dégradation de la couche d'ozone, etc.)) (Payraudeau et al., 2007). L'ACV est basée sur la quantification des flux de matières et d'énergies entrants et sortants du système étudié qui sont ensuite convertis et agrégés en catégories d'impacts en utilisant des modèles mathématiques et des facteurs de caractérisation spécifique pour chaque composante.

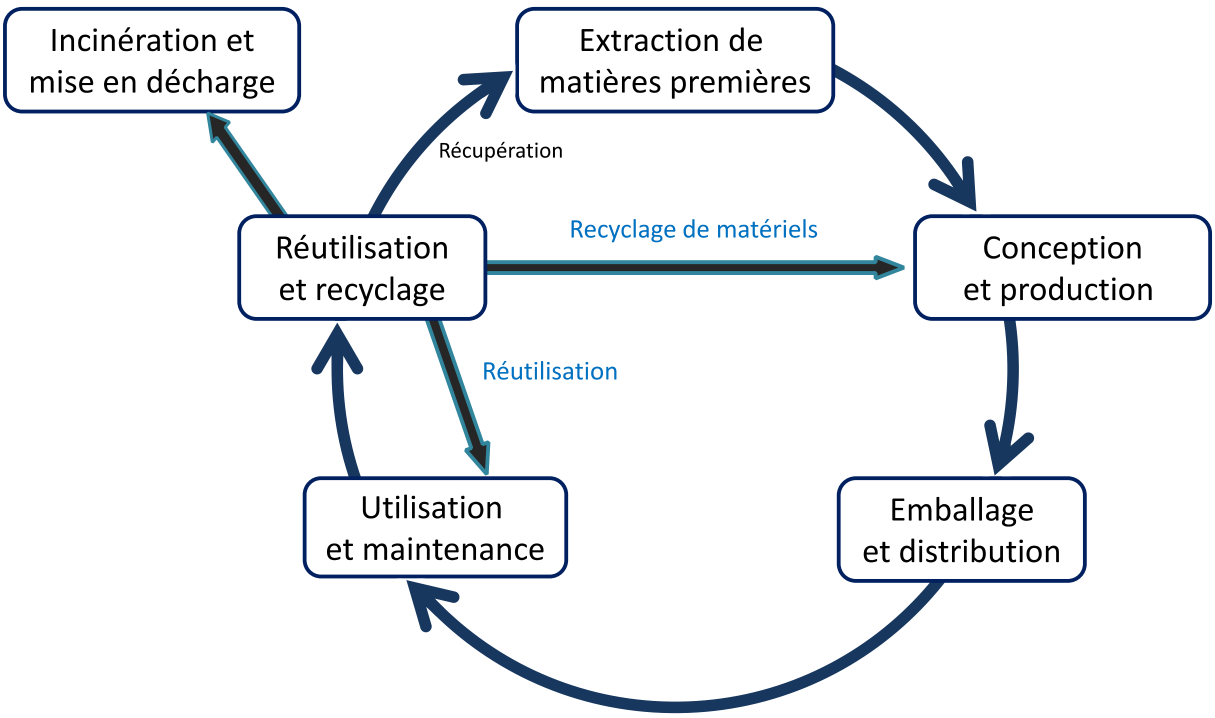


Figure 1.1 : Les étapes du cycle de vie d'un produit (inspiré de UNEP/SETAC (Benoît et al., 2010))

En plus de quantifier les impacts environnementaux, l'ACV est un outil pertinent d'aide à la décision. Elle permet d'identifier les étapes les plus sensibles de la chaîne de production et

de proposer des voies d'amélioration pour réduire les pressions sur l'environnement (Ardente et al., 2005; Jolliet et al., 2010). Le plus souvent, ce cadre méthodologique est utilisé pour la comparaison du profil environnemental de deux produits ou systèmes ayant une fonction identique (Jolliet et al., 2010). La majorité des études en ACV se focalisent sur l'aspect environnemental et néglige l'aspect socio-économique lié au produit, procédé ou service; mais récemment, la méthode ACV a commencé à s'élargir aux domaines économique et social (Benoît et al., 2010).
L'ACV est considérée comme approche universelle qui peut être appliquée dans tous les domaines. À titre d'exemple, l'ACV a été appliquée dans le domaine pharmaceutique pour évaluer le concept de "produits chimiques verts" (green chemicals) (Kralisch et al., 2015), elle a été appliquée à la production de véhicules (traditionnels et électriques) (Hawkins et al., 2013), à des technologies photovoltaïques (Chatzisideris et al., 2016), à la construction des bâtiments (Säynäjoki et al., 2017) etc... L'adaptation de l'ACV au secteur agricole date des années 1990. Elle a été appliquée en production porcine pour comparer différentes modalités de production (McAuliffe et al., 2016; Monteiro et al., 2016; Noya et al., 2017) et en production laitière (Baldini et al., 2017; Stylianou et al., 2016; Valsasina et al., 2017). Des études ACV ont été menées à plusieurs reprises pour évaluer les activités de pêche et d'aquaculture. Parmi les études les plus récentes, on peut citer l'évaluation de l'aquaculture en Égypte (Henriksson et al., 2017), la comparaison entre la monoculture et la polyculture dans les étangs au Brésil (Medeiros et al., 2017), l'évaluation de l'impact de la production d'anchois européen à la senne coulissante (Laso et al., 2017).

Selon la norme ISO 14040 et les recommandations de la SETAC, l'application de l'ACV se fait en quatre phases essentielles (Figure 1.2)(ISO, 2006a): définition des objectifs et du champ d'étude, mise en place et analyse de l'inventaire des extractions et des émissions liées à la fonction étudiée, évaluation des impacts environnementaux et interprétation des résultats. Du fait de son caractère itératif et cyclique, une étape peut amener à revoir une ou plusieurs étapes précédentes pour affiner les hypothèses, les objectifs et le champ d'étude mis en place. Le niveau d'incertitude augmente avec le passage d'une étape à l'autre. En parallèle, la qualité de la communication et l'interprétation des résultats devient de plus en plus complexe avec chaque étape.

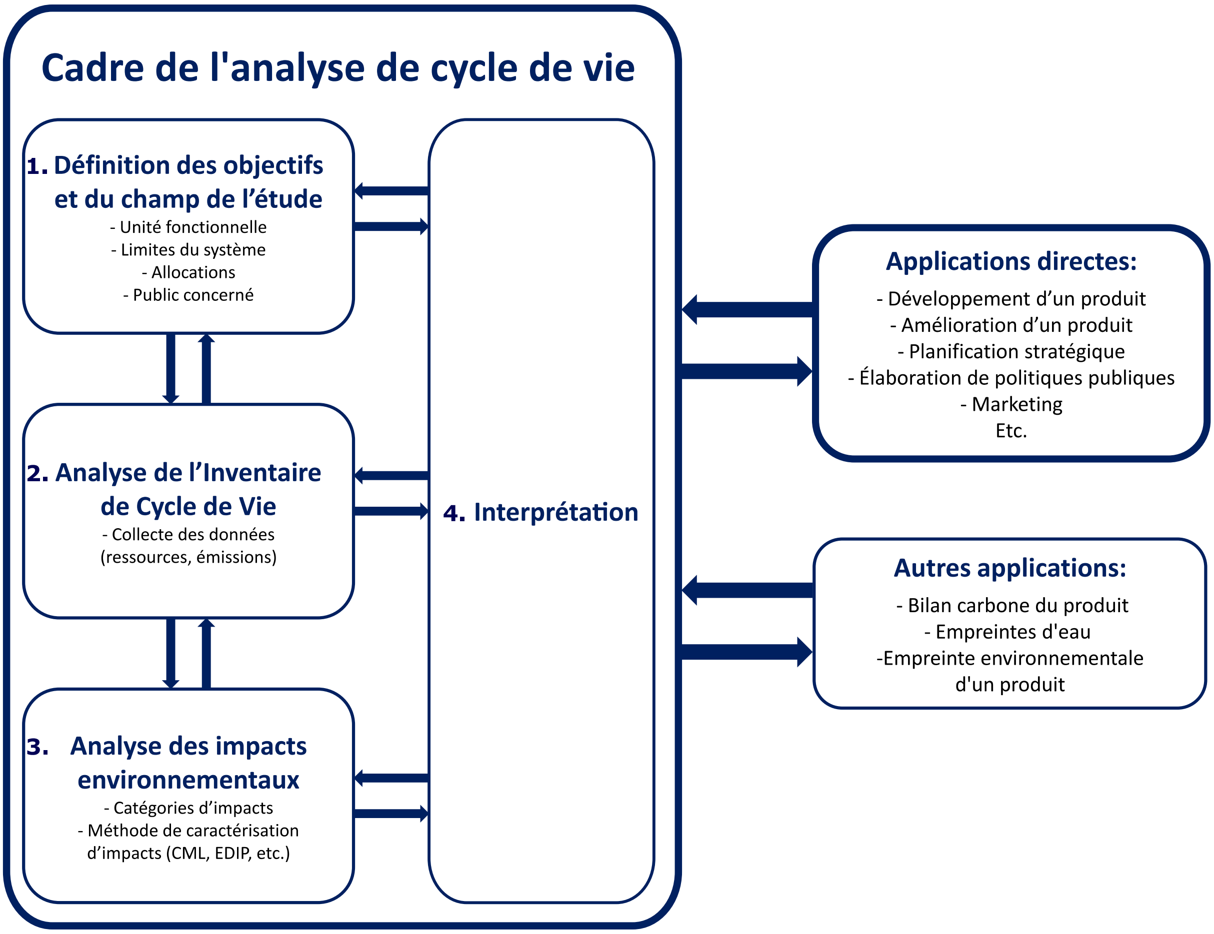


Figure 1.2 : Cadre méthodologique de l'Analyse de Cycle de Vie selon la norme ISO 14044 et applications potentielles de la méthode (inspiré de ISO, (2006a)).

1.2. La définition des objectifs et du champ de l'étude

Cette première étape s'avère cruciale à la réussite de l'ACV. Elle consiste à annoncer clairement les objectifs de l'étude. Il est important de bien décrire et bien définir la finalité de l'analyse puisque de ces objectifs découlent le choix des frontières du système, l'unité fonctionnelle (UF) du produit analysé, le public concerné ainsi que les hypothèses et les limites de l'étude (Jolliet et al., 2010). L'ACV est un outil pertinent pour (i) l'évaluation et l'estimation des impacts environnementaux d'un produit, (ii) la comparaison des impacts environnementaux de deux produits ou d'alternatives de production, (iii) l'amélioration d'un produit en identifiant les processus de production avec le plus de contribution aux impacts.

Le choix de l'unité fonctionnelle doit être fait selon les objectifs visés. L'UF est une grandeur mesurable, précise et additive, qui décrit la fonction principale du système évalué. Tous les flux d'inventaire (ressources et émissions) ainsi que les résultats des impacts prendront cette UF comme référence (Jolliet et al., 2010).

L'évaluation environnementale en utilisant l'ACV est portée sur la fonction du produit et non sur le produit en lui-même. Par exemple il n'est pas judicieux de comparer deux pesticides A et B seulement sur la base des substances nécessaires pour la production, il faut plutôt se baser sur leur fonction. Si le pesticide A génère deux fois moins d'impacts que le pesticide B, mais le pesticide B permet une protection des cultures sur une surface de 50 km^2 alors que le pesticide A ne protège que 25 km^2, il faut multiplier l'impact du pesticide A par deux et finalement l'impact réel des deux pesticides est le même. Donc l'UF doit être la surface protégée par le pesticide. En plus, il faut prendre la composante temps en compte. Par exemple, si les pesticides A et B protègent la même surface, et le pesticide A assure une protection pendant 3 mois alors que le pesticide B protège la culture pour 6 mois, il faut multiplier l'impact du pesticide A par deux pour que ça soit comparable. Donc l'UF doit être la surface protégée par le pesticide pendant une durée déterminée. Ainsi, l'UF doit être choisie afin de comparer des choses comparables. En agriculture, l'UF peut être basée sur la masse produite, telle qu'une tonne de viande, de poisson, de culture ou de lait (Noya et al., 2017; Smetana et al., 2015), en fonction de surface (hectare) (Falcone et al., 2015) ou en fonction monétaire (van der Werf and Salou, 2015).

Après la définition des objectifs de l'étude et l'UF, il nécessaire de décrire les limites du système avec les éléments constitutifs et leurs relations. Le système doit inclure l'ensemble des étapes de production (processus) impliquées dans la réalisation de l'UF et il est généralement représenté sous la forme d'un arbre de processus ou diagramme (Jolliet et al., 2010). Les processus pourront varier selon les objectifs de l'étude. Pour la majorité des ACV en agriculture, le système s'arrête à la sortie de la ferme ("*cradle to gate*" au lieu de "*cradle to grave*")(Nemecek et al., 2007) sans prendre en considération les phases ultérieures de la production (transformation, utilisation, distribution, traitement des déchets, etc.). Il est aussi important de définir les limites géographiques, temporelles et technologiques de l'analyse, puisque les exigences législatives ainsi que les habitudes de consommation varient avec le temps et d'un endroit à l'autre (Guinée et al., 2002). La délimitation du système étudié est cruciale pour la mise en place de l'inventaire des extractions (flux entrants) et émissions (flux sortants) et aussi les impacts considérés dans l'ACV.

La dernière question à traiter dans cette première étape d'ACV est celle des coproduits. En effet, plusieurs systèmes conduisent à la formation de différents produits simultanément (par exemple la production de blé et de paille). Dans le cas de production multiple, il faut allouer (répartir) les matières premières et les impacts environnementaux entre le produit et les coproduits en fonction de paramètres physiques (masses ou contenu énergétique), ou en fonction des paramètres économiques (prix de vente ou bénéfices générés). Selon la norme ISO 14044 (ISO, 2006b) il est préférable d'éviter l'allocation en subdivisant les processus ou par extension du système, sinon il faut utiliser des allocations de masse reflétant les relations physiques sous-jacentes entre produit et coproduits, et en dernier recours utiliser l'allocation économique.

1.3. L'Inventaire de Cycle de Vie (ICV)

Au cours de cette deuxième étape de l'ACV il faut recenser, en se basant sur l'arbre de processus, toutes les ressources et les émissions reliées à chacun des processus impliqués dans la production de l'UF. Généralement, cette étape est la plus consommatrice de temps parce que le recueil des données recherchées est souvent complexe et fastidieux. Du fait que la pertinence de l'analyse environnementale est directement influencée par la qualité et la précision des données inventoriées, il est nécessaire de faire un travail méticuleux en validant minutieusement les données lors de leur collecte et leur traitement.

L'ICV quantifie tous les flux de matières et d'énergie entrants (ressources consommées) et sortants (émissions dans l'air, l'eau et le sol) du système étudié, ils sont ensuite rapportés à l'UF (définie dans l'étape précédente). L'idéal est de mettre en place l'ICV en se basant sur des données issues directement du système étudié via des enquêtes, expérimentations ou à partir de données de littérature. En ce qui concerne les données inaccessibles par des enquêtes ou des mesures, le recours à des sorties de modèles (par exemple le cas des émissions vers l'air, l'eau et le sol) et/ou des dires d'experts est nécessaire. Plusieurs bases de données ont été développées pour fournir des données d'inventaire du niveau régional au niveau global. La base de données la plus utilisée en ACV est EcoInvent (Weidema et al., 2013; Wernet et al., 2016). EcoInvent est le leader international dans le domaine des données d'écobilan. Cette base contient des ICV pour les différents matériaux (chimiques, métaux, matériaux biologiques, etc.), pour l'énergie (électricité, pétrole, charbon, gaz naturel, hydroélectrique, nucléaire, etc.), pour le traitement de déchets (incinération, déposition, etc.), pour les trafics (routier, maritime, aérien, etc.) et même pour les produits et processus agricoles et électroniques.

1.4. L'analyse des impacts environnementaux

L'analyse des impacts environnementaux consiste à agréger les nombreuses ressources et émissions de l'ICV précédemment définie et les convertir en un nombre plus faible d'indicateurs reflétant les impacts environnementaux qui découlent du système étudié en fonction de leurs compartiments cibles (air, eau, sol). Ceci permet de rendre les résultats de l'ICV plus compréhensible et de les exprimer en termes d'impacts environnementaux potentiels. D'après Jolliet et al. (2010)., il existe deux types de catégories d'impacts (Figure 1.3):

- Catégories d'impacts orientées problèmes, ou midpoint : elles reflètent principalement l'importance relative des émissions (CO_2, PO_4, CFC, etc.) d'une substance sur une catégorie d'impact spécifique. À titre d'exemple d'impact midpoint: réchauffement climatique, acidification, eutrophisation, toxicité, etc.
- Catégories d'impacts orientées dommages, ou endpoint : elles reflètent la contribution des catégories d'impacts midpoint à une ou plusieurs catégories endpoint. Ainsi, au lieu de parler des émissions, les catégories d'impacts vont quantifier les effets secondaires des émissions (par exemple : l'augmentation des rayons UV engendrée par la déplétion de l'ozone stratosphérique, peut causer des problèmes de cataracte et de cancer). Il existe trois catégories d'impacts endpoint, épuisement des ressources, impacts sur la santé humaine et impacts écologiques sur les écosystèmes.

Il faut choisir les catégories d'impacts d'une façon pertinente en se basant sur les objectifs de l'étude. Selon la norme ISO 14044 (ISO, 2006b), la sélection des impacts doit se faire selon trois critères principaux : (i) la complétude : il faut prendre en considération tous les impacts environnementaux jugés pertinents, (ii) la non-redondance : il faut que les impacts soient le plus indépendants possible et (iii) la validité : il faut que les modèles de caractérisation des impacts soient reconnus scientifiquement.

La caractérisation correspond à l'agrégation des éléments de l'inventaire en se basant sur des facteurs de caractérisation pour calculer la valeur de chaque catégorie d'impact. Les facteurs de caractérisation sont généralement recensés dans les publications scientifiques et exprimés en fonction d'une molécule de référence. À titre d'exemple, le CO_2 est la substance de référence pour le réchauffement climatique, ainsi toutes les substances participant à cet impact seront converties et exprimées en équivalent CO_2 (par exemple le méthane a un potentiel d'impact 25 fois plus important que le CO_2 vis à vis du réchauffement climatique, donc l'émission d'1 kg de méthane dans l'air induira un réchauffement climatique de 25 kg de CO_2-équivalent).

Il existe plusieurs méthodes opérationnelles avec des valeurs de facteurs de caractérisation déjà calculés. Les méthodes les plus utilisées sont:

- CML (Guinée et al., 2002) : cette méthode détermine le potentiel d'impact de chaque polluant sans tenir compte de son cheminement dans l'environnement. De ce fait, le devenir des polluants et la sensibilité de l'environnement sont considérés comme maximums (tout ce qui est émis cause un impact). C'est une méthode orienté problème.
- EDIP 2003 (Hauschild and Potting, 2010) : cette méthode est la plus précise pour certains impacts, puisqu'elle prend en considération la différentiation spatiale des quelques catégories d'impacts (exemple : acidification).
- Impact 2002+ (Jolliet et al., 2003) : cette méthode combine une approche orientée problème et une approche orientée dommage en agrégeant 14 impacts midpoint en 4 impacts endpoint (santé humaine, qualité des écosystèmes, changement climatique et ressources).
- La méthode ReCiPe (Goedkoop et al., 2009) : cette méthode combine également des impacts midpoint et endpoint. Elle propose des impacts endpoint agrégés pour décrire l'atteinte aux écosystèmes en nombre d'espèces par année, la santé humaine en nombre de jours de vie en bonne santé (DALY), l'atteinte aux ressources en

excédant de coût. Les trois indicateurs sont ensuite agrégés pour donner un seul score final.

- ILCD 2011 : il s'agit d'une méthode midpoint développée par la commission Européenne (European Commission, 2010) et qui a pour objectif de standardiser le calcul des impacts. Cette méthode reprend un certain nombre de catégories d'impact produites dans d'autres méthodes.

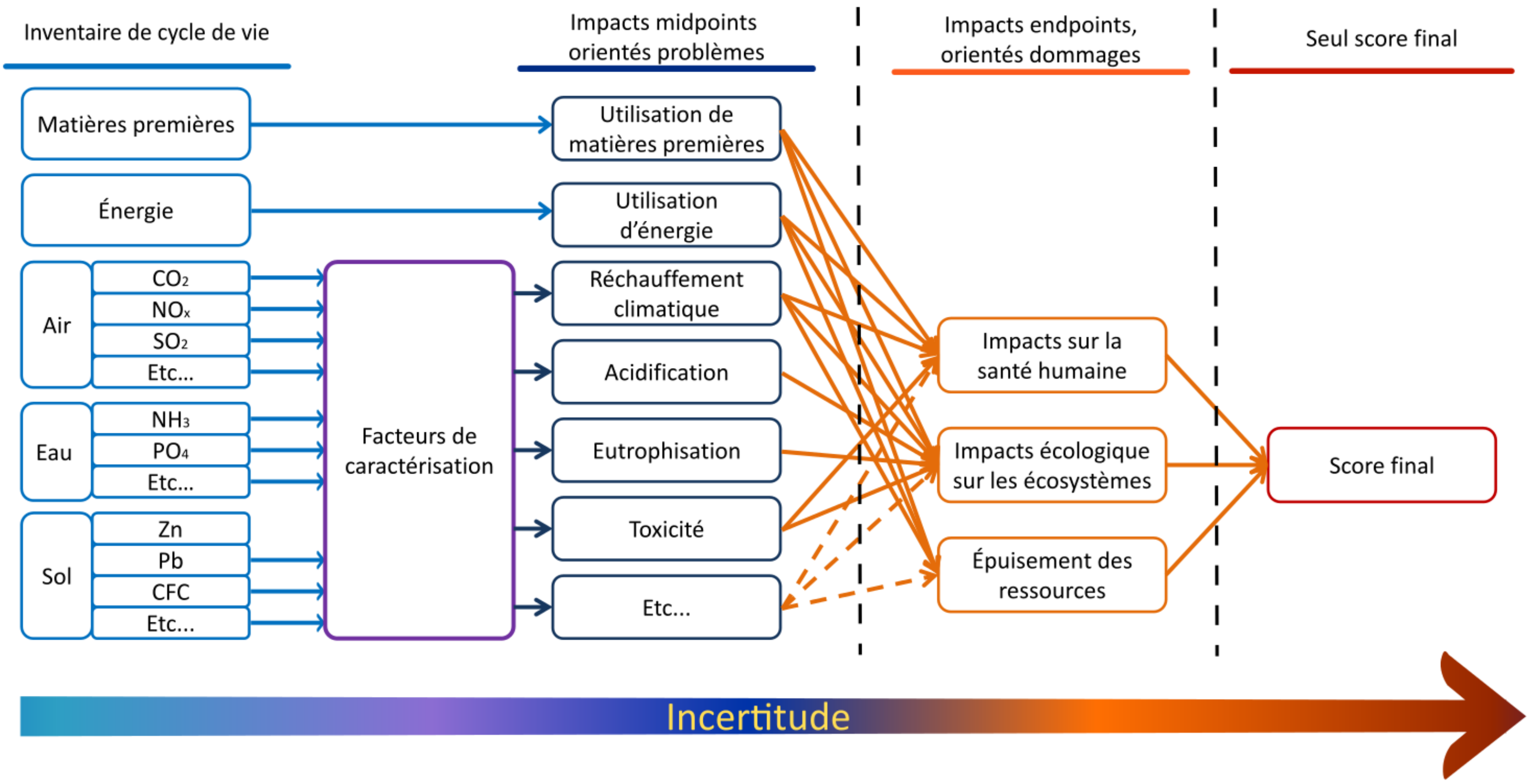


Figure 1.3 : Structure de l'analyse de cycle de vie pour estimer les impacts environnementaux (inspiré de (ISO, 2006a)).

La norme ISO 14044 (ISO, 2006b) indique que la comparaison entre les différentes catégories d'impact doit se faire sur 3 étapes : (i) la normalisation des résultats pour exprimer les impacts selon une même unité; (ii) le groupement en attribuant qualitativement des rangs d'importance aux impacts et (iii) la pondération pour agréger les résultats normalisés par un facteur de pondération (Jolliet et al., 2010; Udo de Haes et al., 2002). La méthode de normalisation doit être appliquée avec précaution (Reap et al., 2008).

1.5. Interprétation

La dernière étape de l'ACV est l'interprétation des résultats. Au cours de cette phase, les résultats d'impacts environnementaux sont analysés et évalués et ensuite combinés en cohérence avec les objectifs de l'étude afin de tirer des conclusions et des recommandations (Blanc and Labouze, 1999). À ce niveau, des analyses de l'incertitude, de la qualité et de la robustesse des données utilisées ainsi que des résultats obtenus peuvent être réalisées. Les sources d'incertitudes en ACV sont nombreuses et récurrentes à chaque étape. Au niveau de l'ICV, les incertitudes sont liées à la récolte des données et les modèles d'estimations des sortants utilisés, et elles sont associées aux facteurs de caractérisations au niveau de la phase de l'analyse de cycle de vie. Étant donné le caractère itératif de l'ACV, il est courant de faire des modifications en retournant aux étapes précédentes pour affiner les résultats ; pour cela, l'interprétation doit se faire après chaque phase de l'ACV (Jolliet et al., 2010). Cette étape permet aussi l'identification des processus du cycle de vie du produit qui contribuent le plus aux impacts environnementaux. Cette analyse de contribution permet de mieux comprendre le fonctionnement du système et permet de proposer des leviers applicables pour l'amélioration environnementale du système. À ce stade, il est aussi possible de tester et évaluer des scénarios alternatifs pour certains processus de la production. Pour remédier au manque de valeurs de référence pour les produits et les impacts, une comparaison des impacts environnementaux de différents systèmes de production ou bien à une analyse de sensibilité peuvent être conduites pour mieux sélectionner les axes d'amélioration et les processus à faire évoluer en premier.

1.6. Conclusion du chapitre

Ce chapitre détaille le cadre méthodologique de l'ACV et fait ressortir son caractère holistique. C'est une méthode exhaustive et globale qui prend en compte l'intégralité d'un système de production (les ressources et les émissions) ainsi que les impacts environnementaux associés à chaque processus inclus dans la fabrication du produit. Il s'agit de la seule méthode d’analyse environnementale qui permet de lier l’impact environnemental à la fonction d’un produit. Allant au-delà d’une simple description, cette approche peut être utilisée pour faire émerger des voies d’amélioration des systèmes de production (Jolliet et al., 2010). L'ACV s'articule essentiellement autour de quatre étapes (i) la définition des objectifs et du champ d'étude où il faut mentionner les objectifs de l'analyse environnementale, délimiter le système de production à étudier (identifier les processus à inclure et à exclure), et choisir l'unité fonctionnelle ; (ii) la mise en place de l'inventaire de cycle de vie qui recueille l'ensemble de ressources et d'émissions associées à la production de l'unité fonctionnelle ; (iii) l'analyse des impacts environnementaux qui permet de transformer les données déjà inventoriées en impacts sur l'environnement après sélection des impacts à étudier et la méthode de calcul à appliquer ; (v) l'interprétation des résultats qui permet de vérifier les données et de proposer des conclusions et des recommandations.

Bien que l'ACV propose plusieurs indicateurs d'impact allant de l'échelle locale (eutrophisation), aux échelles régionale (acidification) et globale (réchauffement climatique), il existe encore des lacunes lorsqu'il s'agit des impacts associés aux produits de la mer, notamment les impacts sur les ressources biologiques en mer, sur les fonds marins et sur l'utilisation de l'espace marin (Pelletier et al., 2007). L'ACV a aussi certaines limites inhérentes à la méthode, comme la mauvaise prise en compte de la variation temporelle et spatiale lors du calcul d'impacts, la qualité des données utilisées qui influencent directement la qualité de l'analyse environnementale, et l'utilisation des données génériques ce qui résulte en la non-prise en compte des aspects spécifiques liés au site de production (Guinee et al., 2010).

Résumé graphique du chapitre

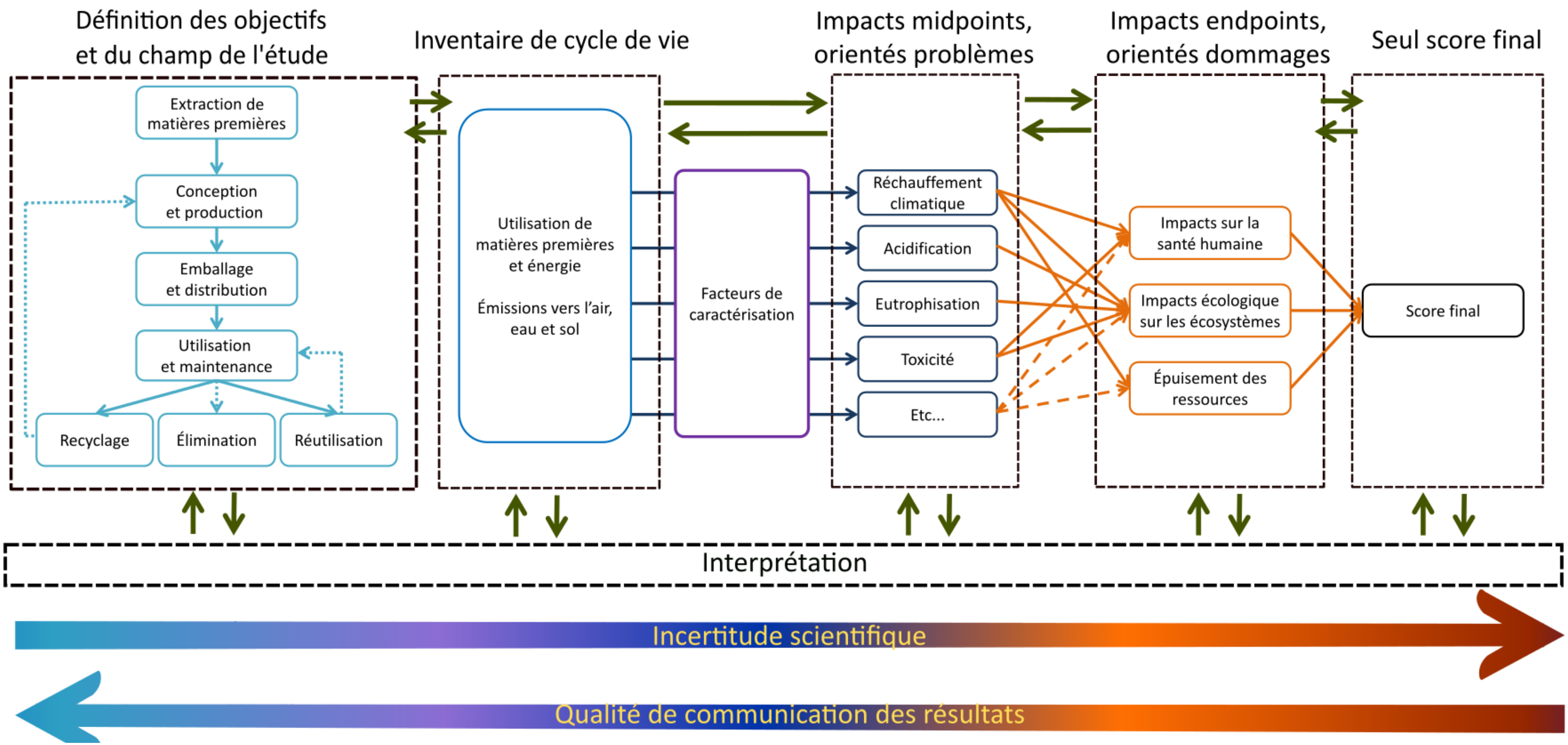


Figure 1.4 : Structure et étapes de l'analyse de cycle de vie pour estimer les impacts environnementaux (inspiré de ISO (2006a) et UNEP/SETAC (Benoît et al., 2010)).

Chapitre 2

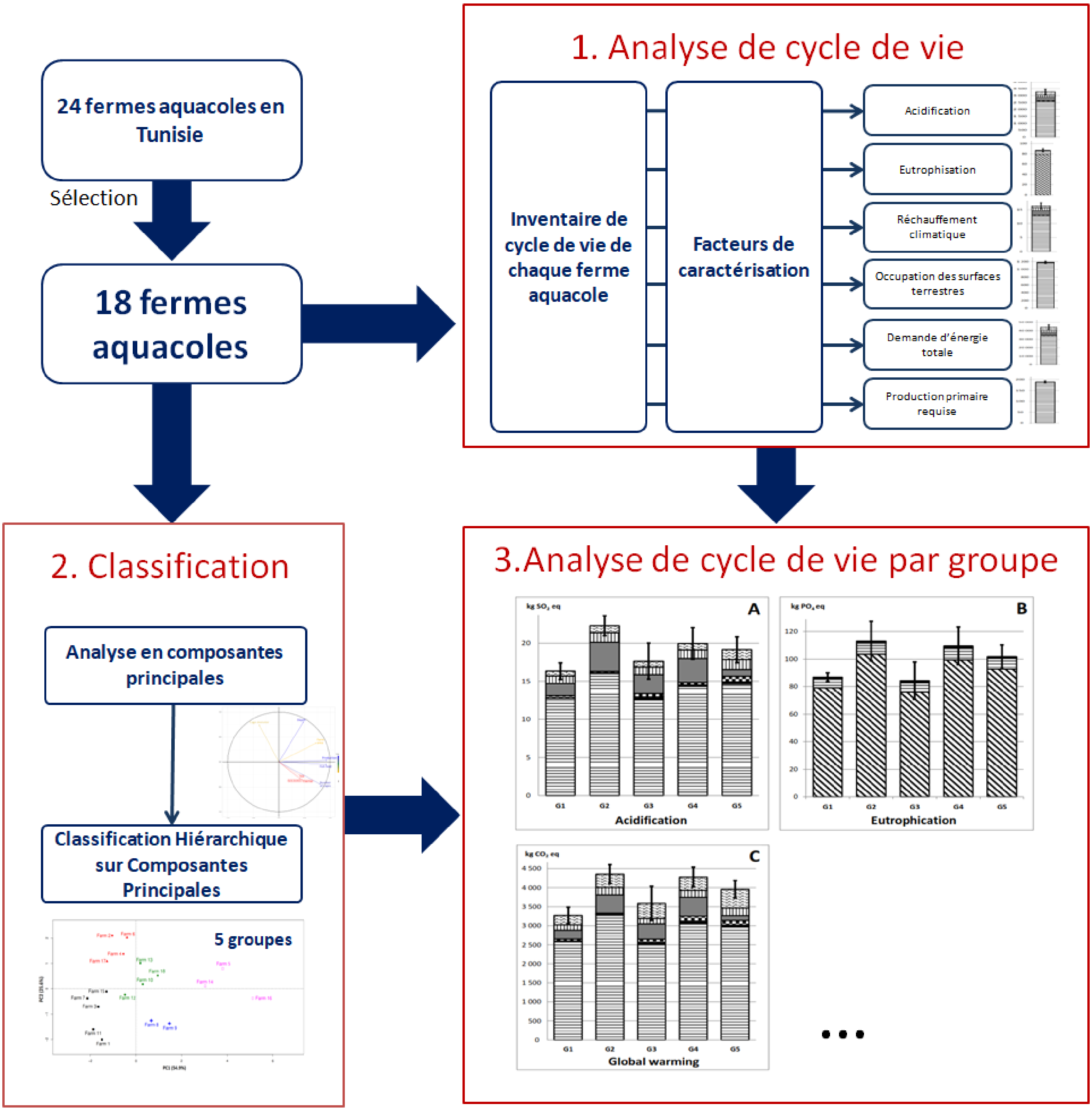
Application de l'Analyse du Cycle de Vie au secteur aquacole en Tunisie

2.1. Introduction du chapitre

Ce chapitre se focalise sur l'application et l'adaptation de la méthode de l'ACV au domaine aquacole en Tunisie. Le premier objectif du chapitre est d'étudier les impacts environnementaux reliés à l'aquaculture et de déterminer la contribution aux impacts environnementaux de chaque composante intervenant dans l'élevage. Le second objectif est d'identifier les pratiques à améliorer et de faire des recommandations de solutions pour un meilleur bilan environnemental. Le chapitre s'articule autour de deux articles scientifiques publiés en 2017.

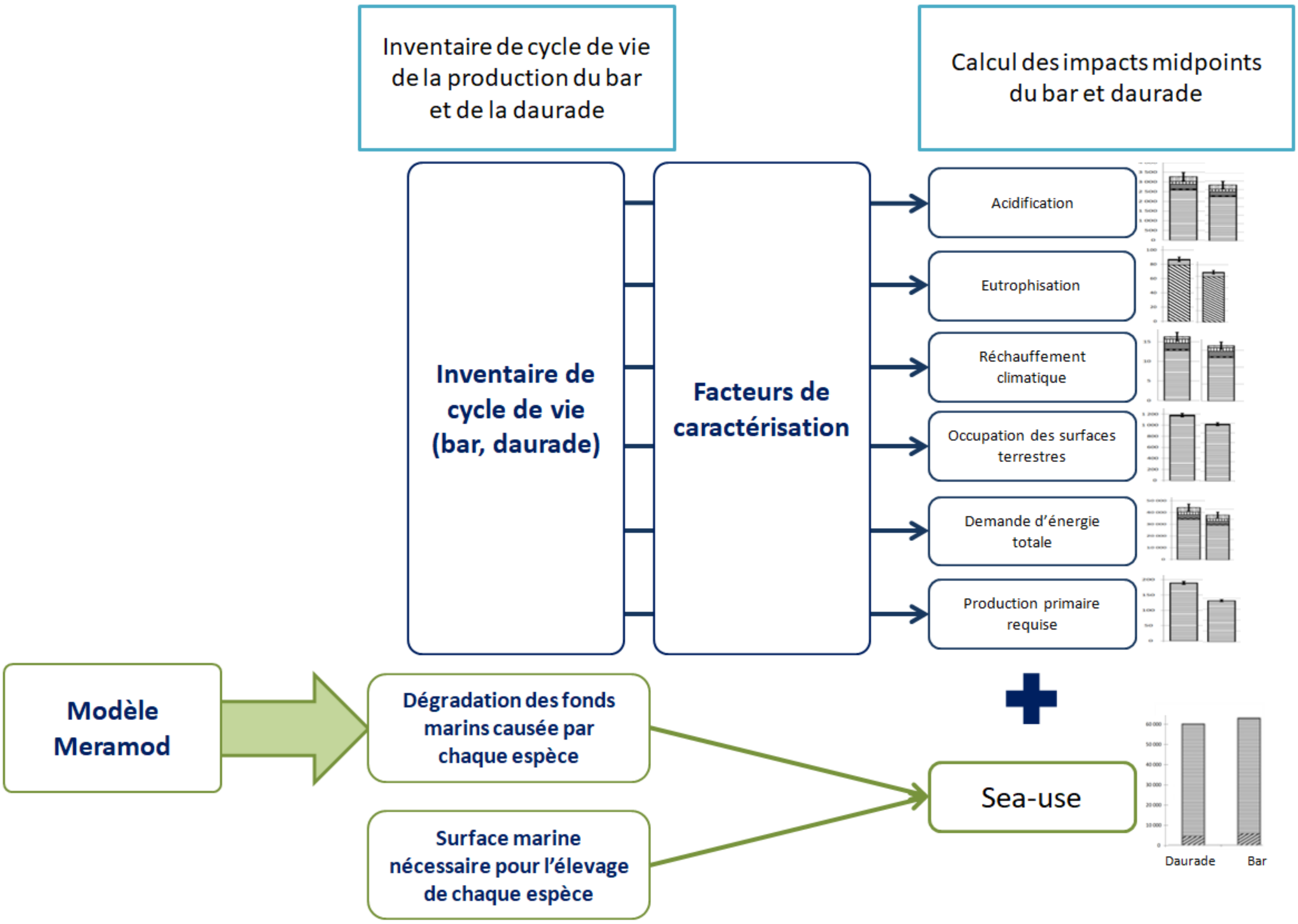
Le premier article publié dans "the International Journal of Life Cycle Assessment" (manuscrit A, Abdou et al. (2017a), section 2.2 du présent chapitre), a permis de comprendre l'influence de la variabilité des pratiques d'élevage aquacole sur le bilan environnemental des fermes d'aquaculture. Parmi les 24 fermes aquacoles qui existent en Tunisie, 18 fermes ont été sélectionnées dans cette étude selon leurs spécialisations et la méthode d'élevage adoptée. Les fermes étudiées sont spécialisées dans l'élevage intensif du bar (*Dicentrarchus labrax*) et de la daurade (*Sparus aurata*) dans des cages en mer. Les fermes aquacoles sélectionnées ont ensuite été classifiées en se basant sur les plus importantes caractéristiques d'élevage (surface de ferme, production annuelle, nombre de cages, diamètres des cages, etc) en utilisant une Analyse en Composantes Principales (ACP) suivie d'une Classification Hiérarchique sur Composantes Principales (CHCP). Cette méthode de classification n'a jamais été utilisée dans les études ACV des produits de mer puisque la classification se fait généralement sur la base d'une seule caractéristique technique d'élevage aquacole (production, surface, etc). L'ACV a été appliquée à chacune des fermes incluses dans l'étude et les résultats des impacts et des contributions ont été calculés par groupe de fermes d'aquaculture. Six catégories d'impacts ont été incluses : acidification, eutrophisation, réchauffement climatique, occupation des surfaces terrestres, demande d'énergie cumulée et production primaire nette.

Résumé graphique de la méthodologie utilisée dans le manuscrit A (Abdou et al., 2017a)



Le deuxième article de ce chapitre est publié dans le journal "Aquaculture" (manuscrit B, Abdou et al. (2017b), section 2.3 du présent chapitre). Cette partie s'appuie sur l'application d'une ACV plus spécifique en étudiant l'impact environnemental lié à une seule ferme aquacole spécialisée dans l'élevage intensif du bar (*Dicentrarchus labrax*) et de la daurade (*Sparus aurata*) dans des cages en mer en Tunisie. L'objectif de ce papier est de comparer les impacts environnementaux de l'élevage du bar et de la daurade. La ferme aquacole étudiée produit 2 000 tonnes de poisson par an (630 tonnes du bar et 1470 tonnes de daurades). En plus des catégories d'impacts incluses dans le premier article, des propositions d'améliorations ont été formulées pour ajuster la catégorie "sea-use" et l'adapter au secteur aquacole. Cette catégorie permet de mieux évaluer l'impact de l'occupation de l'espace marin et l'impact de l'activité d'aquaculture sur les fonds. Pour cela, un modèle MERAMOD a été mis en place permettant de quantifier la dégradation des fonds marins causée par la ferme aquacole.

Résumé graphique de la méthodologie utilisée dans le manuscrit B (Abdou et al., 2017b)



2.2. Manuscrit A "Rearing performances and environmental assessment of sea cage farming in Tunisia using life cycle assessment (LCA) combined with PCA and HCPC"

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Abstract

Purpose The present study aims to understand the influence of rearing practices and the contributions of production phases of fish farming to their environmental impacts and determine which practices and technical characteristics can best improve the farms' environmental performance. Another objective is to identify the influence of variability in farming practices on the environmental performances of sea cage aquaculture farms of seabass and seabream in Tunisia by using Principal Component Analysis (PCA) and Hierarchical Clustering on Principal Components (HCPC) methods and then combining the classification with life cycle assessment (LCA)

Methods The approach consisted of three major steps: (i) of the 24 aquaculture farms in Tunisia, 18 were selected which follow intensive rearing practices in sea cages of European seabass (*Dicentrarchus labrax*) and gilthead seabream (*Sparus aurata*) and then a typology was developed to classify the studied farms into rearing practice groups using HCPC; (ii) LCA was performed on each aquaculture farm; and (iii) mean impacts and contributions of production phases were calculated for each group of farms. Impact categories included acidification, eutrophication, global warming, land occupation, total cumulative energy demand and net primary production use.

Results and discussion Results revealed high correlation between rearing practices and impacts. The feed-conversion ratio (FCR), water column depth under the cages and cage size had the greatest influence on impact intensity. Rearing practices and fish feed were the greatest contributors to the impacts studied due to the production of fish meal and oil and the low efficiency of feed use, which generated large amounts of nitrogen and phosphorus emissions. It is necessary to optimise the diet formulation and to follow better feeding strategies to lower the FCR and improve farm performance. Water column depth greatly influenced the farms' environmental performance due to the increase in waste dispersion at deeper depths, while shallow depths resulted in accumulation of organic matter and degradation of water quality. Cage size influences environmental performances of aquaculture farms. Thus, from an environmental viewpoint, decision makers should grant licenses for farms in deeper water with larger cages, and encourage them to improve their FCRs.

Conclusions This study is the first attempt to combine the HCPC method and the LCA framework to study the environmental performance of aquacultural activity. The typology developed captures the variability among farms because it considers several farm characteristics in the classification. The LCA demonstrated that technical parameters in need of improvement are related to the technical expertise of farm managers and workers and to the location of the farm.

Keywords: Marine aquaculture, Life cycle assessment (LCA), Environmental impact, Tunisia, Typology.

2.2.1. Introduction

Fish farming is considered the fastest growing animal food production sector worldwide (FAO, 2016), and aquatic products play a growing role in human nutrition. World demand for seafood increased from 9.9 kg per capita in the 1960s to 19.7 kg in 2013, with preliminary estimates exceeding 20 kg per capita in 2014 (FAO, 2016). Fisheries remained stable over the last three decades and can no longer meet the increase in demand; however, aquaculture production experienced substantial growth from 2009-2014 (by an average of 23.5%) (FAO, 2016). Currently, approximately 44% of fish consumed are farmed, and this percentage is predicted to surpass that of fisheries in 2021 and reach 52% by 2025 (FAO, 2016). Aquaculture carries the risk of negative impacts on the environment surrounding the farm by emitting pollutants and waste (Read and Fernandes, 2003), which can change ecosystems and influence biodiversity (Tovar et al., 2000). Aquaculture farms have a relatively wide variety of environmental impacts due to their use of natural resources from different ecosystems (e.g. fish feed, raw material) (Naylor et al., 2000).

Located in northern Africa on the southern coast of the Mediterranean, Tunisia has more than 1,300 km of coastline. Fisheries and aquaculture play an important role both in socio-economic terms and as a food source. As a consequence, fish consumption in Tunisia has increased by 32% since 1990, and annual fish consumption reached 9.5 kg per capita in 2014 (FAO 2016). Aquacultural activity is marine-oriented, and annual production exceeded 10,000 tons in 2014. The number of fish farms increased from only 7 in 2009 to 24 in 2014 (DGPA 2014). The most important reared species in terms of economic value are European seabass (*Dicentrarchus labrax*) and gilthead seabream (*Sparus aurata*), for which prices per kg range from US$3.90-$5.20 and US$3.50-$4.30, respectively (FAO 2016). In light of the current socio-economic and environmental context, minimising environmental impacts of aquaculture is under close scrutiny, and properly assessing them is crucial for sustainable development. Several approaches are possible, such as using environmental indictors of sustainability, ecological or carbon footprints, risk assessment, estimates of waste outputs, using biological and chemical-physical measurements, and life cycle assessment (LCA). LCA was performed in this study to assess environmental impacts of sea cage aquaculture in Tunisia.

LCA is a standardised analytical method (ISO 2006a; ISO 2006b) to assess impacts from "cradle-to-grave", i.e. from raw material extraction, manufacturing and use, to waste management and recycling or disposal (Guinée et al., 2002). It provides a complete view of connections between production systems and the environment. Most environmental studies focus solely on local impacts of aquaculture farms and ignore other important impacts related to industrial processes involved in fish farming. The use of this framework in aquaculture has increased worldwide, from only two scientific publications in 2004 to more than 23 in 2012 (Aubin, 2013). Some studies considered several aquaculture farms, classified them into groups of similar farms and then performed LCA of the groups. However, the classification was usually based on only one technical criterion. For example, (Chen et al., 2015) classified production systems into three categories based solely on the size of fish produced, while (Aubin et al., 2015) classified production systems into small and large farms according to pond size. Because these classifications are based on one simple descriptive variable, they do not capture all of the variability within the systems studied, which results in important information being omitted. Classifications based solely on one characteristic (e.g. size of the fish produced, size of the aquaculture farm) do not consider other relevant technical aspects of the activity (e.g. feed-conversion ratio (FCR), feed quantity). Rather than using such a traditional classification method (Lazard et al., 2010), classification should be based on several characteristics and use multifactor statistical analysis to provide more accurate explanation of variability within a given sector. Principal Component Analysis (PCA) and Hierarchical Clustering on Principal Components (HCPC) are multifactor classification methods that better identify the parameters that contribute most to variability in a dataset.

The objective of the present study is to capture the influence of variability in farming practices on the environmental performance of sea cage aquaculture farms of seabass and seabream in Tunisia by using PCA and HCPC in combination with LCA. To our knowledge, this is the first time HCPC and LCA have been combined to study environmental impacts in aquaculture; thus, it is the first attempt to use a novel hierarchical clustering approach before performing LCA of aquaculture farms.

2.2.2. Materials and methods

The method described in this article comprised three steps (Figure 2.1): (i) cluster selected farms using PCA and HCPC, (ii) perform LCA of each farm and (iii) average LCA results per group of farms.

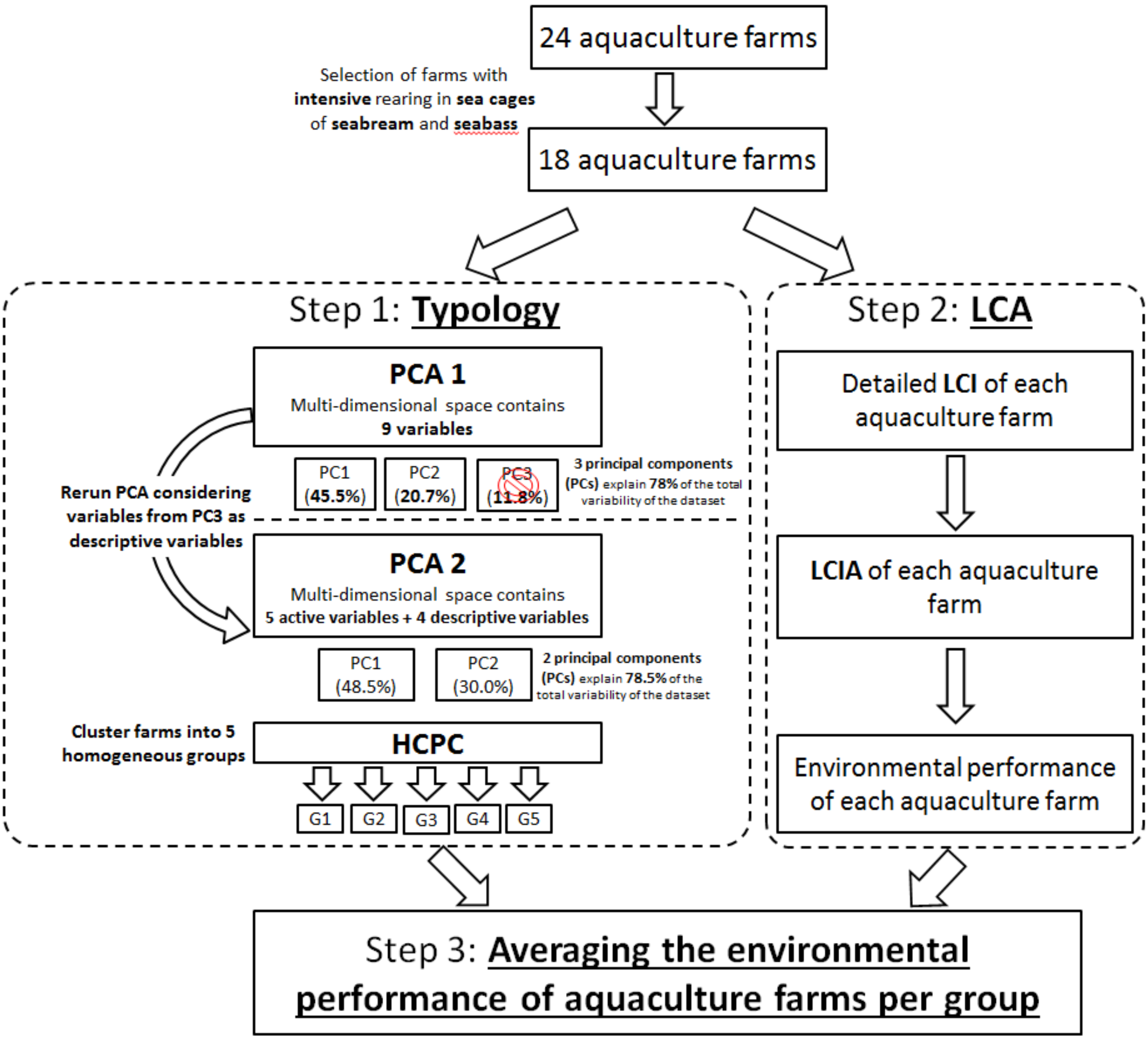


Figure 2.1 : Diagram representing data treatment in this study. PCA: Principal Component Analysis, HCPC: Hierarchical Clustering on Principal Components.

2.2.2.1. Typology development

We selected 18 aquaculture farms (out of the existing 24) that only follow intensive rearing practices of seabass and seabream in sea cages. Data were collected from the Tunisian Department of Fisheries and Aquaculture (DGPA, Direction Générale de la Pêche et de l'Aquacuture) and were used in PCA to characterise the fish farms.

PCA is one of the most popular multivariate statistical techniques (Abdi and Williams, 2010) and is considered an effective approach to reduce the dimensionality of several correlated variables in a new set of orthogonal variables called principal components (PCs). PCs contain the most relevant information and explain as much variability in the dataset as possible. We used PCA to identify the most representative farm characteristics. Each variable is associated with a point whose coordinate on the PC axis is the measure of correlation between the variable and the PC (maximum correlation is 1). The variables are then projected onto a circle of radius 1 called the correlation circle, and the nearer they are near the edge of the circle; the more they are represented by the PC. We retained only PCs of the PCA whose 95% confidence interval for eigenvalues exceeded 1, which included the maximum variance.

We performed a first PCA (PCA 1) based on nine of the most important farm characteristics:

- total area (range: 24-84 ha)
- annual production (range: 480-2,600 t)
- number of cages (15 on small farms and up to 90 on large farms)
- diameter of cages (22, 25 or 29 m)
- water column depth (range: 20-40 m)
- quantity of fish feed required (range: 750-5,000 t); this variability is directly related to the FCR
- FCR (t of feed provided divided by ton of fish produced), which reflects efficiency of the feeding strategy. The observed FCR ranges from 1.4-2.3 for seabream and 1.6-3.0 for seabass.
- duration of the production cycle (range: 10-14 months for seabream and 10-18 months for seabass); this variability is directly related to rearing conditions and the FCR
- number of fingerlings (range: 960,000-6,540,000)

We reran the PCA (PCA 2) and considered the three FCR-related variables as descriptive variables that did not explain the dataset. Individuals (aquaculture farms) were then distributed on the PC factorial map (i.e. PC1 vs. PC2), based on their mean scores on the PCs for variables included. Then, HCPC was performed to classify the 18 farms into small groups based on the PCs. The HCPC method was used to develop a typology that more accurately describes technical differences among farms and captures the variability in technical characteristics of farms across Tunisia (e.g. size, production, rearing practices, species cultivated). HCPC clusters individuals into groups based on the distance (i.e. inherent similarity) between them using Ward's minimum variance criterion to minimize the total within-cluster variance. The first PCs of PCA extract essential information from the dataset, while the last PCs are restricted to noise (less important information). Using HCPC to develop a typology based on PCA 2 provided a more consistent and accurate classification than that obtained from PCA 1 because noise was excluded from the analysis. “Average linkage clustering” was used in HCPC to determine groups by averaging differences between farms. The typology reflects the maximum variability in the dataset because it groups aquaculture farms according to multiple similarities (not based on only one characteristic).

For each type of farm, a coefficient of variation (CV) was calculated for the nine technical characteristics and for the estimated impacts. The CV is a standardised measure of the dispersion within each group, calculated by dividing the standard deviation by the mean and is expressed as a percentage. We used Student’s t-tests to identify significant differences in mean impacts between groups. We chose the Student t-test because impacts followed a normal distribution. To support PCA and HCPC results, we also calculated Spearman's rank correlation coefficients ("rho") between technical. The Spearman coefficient of correlation measures the strength and direction of association between two ranked variables. It is calculated by dividing the covariance of the two variables by the product of their standard deviations. It ranges from -1 for a perfect negative correlation (i.e. an increase in one parameter causes the decrease in the other and vice-versa) to 1 for a perfect positive correlation (i.e. an increase in one parameter causes an increase in the other and vice-versa); a value of 0 implies that there is no linear correlation between the variables (Spearman, 1904). This test was chosen because it is non-parametric (not influenced by the sample distribution) (certain farm characteristics had non-normal distributions) and can be applied to small samples (Gauthier, 2001). All statistical calculations were calculated using R software (R Core Team, 2016). The FactoMineR package was used for PCA and HCPC (Lê et al., 2008).

2.2.2.2. Life cycle assessment

LCA was performed following the four steps recommended by the International Reference Life Cycle Data System (European Commission, 2010): (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment and (iv) interpretation.

2.2.2.2.1. Goal and scope

The goal of this LCA is to estimate environmental impacts associated with aquaculture in Tunisia. The study assesses different rearing practices and the contribution of each phase of fish farming to environmental impacts. Choosing the appropriate functional unit with which to express all impacts is crucial; the functional unit for this study is "one ton of live fish". This LCA is a "cradle-to-gate" assessment because the final product is one ton of fish at the fish farm gate. The system assessed includes many processes involved in fish production, namely: fish feed production and import, infrastructure, transportation of material, fingerlings production and import. The maintenance phase was not considered in this study. We also excluded several post-farm phases (e.g. sorting and packaging, sale, use, disposal at the end of life) due to lack of reliable data (Figure 2.2). We did not allocate impacts between the two co-products (i.e. species) of each system and they were merged into a single product (“fish”). Inputs and outputs related to the rearing operation could not be specified for each species individually because farmers usually rear both species simultaneously. The inventory was compiled and environmental impacts were predicted for each individual farm. Results were then averaged for each group defined by the PCA/HCPC method.

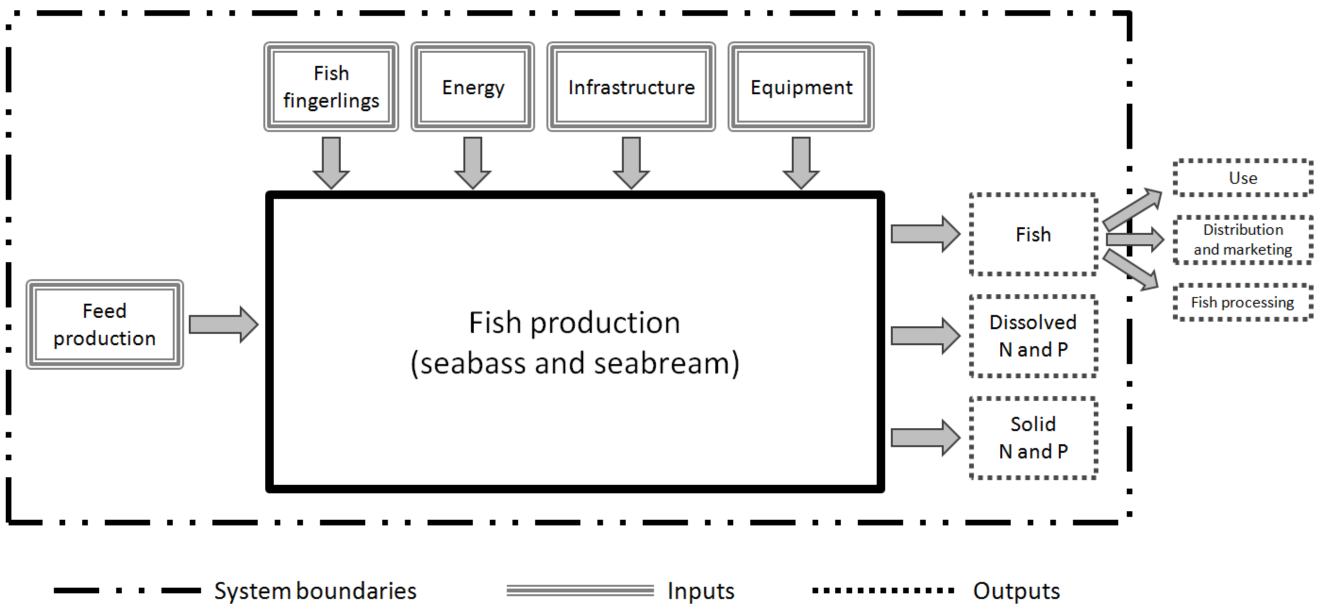


Figure 2.2 : Flow diagram representing phases of the aquaculture system studied

2.2.2.2.2. Life cycle inventory

LCI data were obtained from the Tunisian Department of Fisheries and Aquaculture. Data on farm production (species cultivated, quantity of each species produced, and quantity of fish feed required), inputs required for production (quantity and origin of fish feed, number and origin of fingerlings, and energy required), infrastructure, equipment (number and characteristics of cages, vessels, and machines), and socio-economic information (labour and investment costs) were based on one year of production for each aquaculture farm. For validation and to obtain more detailed data, several field trips were taken to the studied farms, and interviews were conducted with their managers and workers. All aquaculture farms in Tunisia use the same fish feed (the brand name is confidential). Data on fish feed ingredients and chemical composition were based on commercial labels and were supplemented with centesimal analysis (in the central laboratory in Tunisia for cattle-feed analysis). The analysis provided the percentages of ingredients used in 1 kg of fish feed. The fish meal and fish oil used as fish feed ingredients were produced from Peruvian *anchoveta* (*Engraulis ringens*) (Fréon et al., 2014). The plant-based ingredients came mainly from French agriculture (Appendix 2.1). We had access to confidential data provided by the fish-feed-mill manager and nutritionist to validate data about ingredient quantities and origins.

Background data (e.g. electricity use and transport) were extracted from the ecoinvent 3.0 database.

For the outputs, a mass-balance model was used to predict nutrients emitted by the aquaculture farms (Cho and Kaushik, 1990). This method was adapted in several LCA studies and was validated for different species and production systems (Bureau et al. 2003; Aubin et al. 2009; Mungkung et al. 2013; Abdou et al. 2017). Emissions are mainly two forms (solid or dissolved) of metabolic waste containing nitrogen (N) and phosphorus (P). N and P emissions were calculated as the nutrients provided minus those assimilated into fish weight gain, considering feed digestibility, fish body composition and uneaten feed. We estimated theoretical oxygen demand (ThOD), which is the amount of oxygen required to oxidise emitted organic feed compounds (protein, carbohydrates, lipids and fibre) according to the chemical oxygen demand. Detailed inventory process and values used can be found in Supplementary material (Appendix 2.2).

2.2.2.2.3. Life cycle impact assessment

LCI data for each farm were aggregated into impact categories and expressed per ton of fish produced. Environmental impacts were quantified using a characterisation factor (CF) and were assigned to the selected impact categories. Environmental impacts were calculated using SimaPro® 8.0 software (Pré Consultants, 1997).

In agreement with guidelines for aquaculture LCA studies (Abdou et al., 2017b; Aubin et al., 2009; Jerbi et al., 2012; Mungkung et al., 2013), baseline impact categories were selected to address several negative environmental impacts generated by farming activity:

- Acidification: negative impact of fish production on water and soil; it is expressed in kg SO_2 equivalent (eq) and was estimated using mean CFs for European acidification potential (Huijbregts, 1999).
- Eutrophication: negative impact caused by excessive amounts of nutrients in the environment; it is expressed in kg PO_4 eq and was estimated based on CFs proposed by Impact World+ (Helmes 2012).
- Global warming: impact of greenhouse gas emissions on the atmosphere's ability to absorb heat radiation; it is expressed in kg CO_2 eq, and CFs correspond to global warming

potentials over a 100-year horizon (GWP_{100}) recommended by the Intergovernmental Panel on Climate Change (IPCC, 2014).

- Land occupation: terrestrial area required to produce the functional unit; it is expressed in m^2 year. CFs in this category equal one because they represent the land area used in supply chains.
- Net primary production use (NPPuse): the amount of carbon (C) in terrestrial and marine primary production required as a biotic resource for fish production; it is expressed in ton of C and was estimated based on Papatryphon et al. (2004). CFs in this category equal one because they represent the amount of net primary production required for production. We estimated the C content in plant-based ingredients (g C per kg of crop dry matter) and used wet weights (M) and trophic levels of marine organisms (T) to estimate the NPPuse of fishery-derived ingredients: NPPuse = (M/9) × 10(T-1) (Pauly and Christensen, 1995).
- Total cumulative energy demand (TCED): the amount of energy (e.g. fossil fuels, wood, electricity) required for fish production; it is expressed in MJ, and CFs equal lower heating values available in SimaPro.

2.2.3. Results

2.2.3.1. PCA and HCPC results

The first three PCs of PCA-1 explained 78% of total variation in the sample of aquaculture farms. The third PC was responsible only for 11.8% of the total variation and essentially reflected FCR-related variables (FCR, number of fingerlings, and duration of the production cycle). PCA 2 results showed that PC1 and PC2 explained 78.5% of total variation in characteristics of the aquaculture farms sampled. PC1 explained 54.9% of total variation, and significance tests indicated that it was mainly associated with annual production, quantity of fish feed required, total area and number of cages. PC2 explained 25.6% of the total variation, which was associated with water column depth and cage diameter (Figure 2.3).

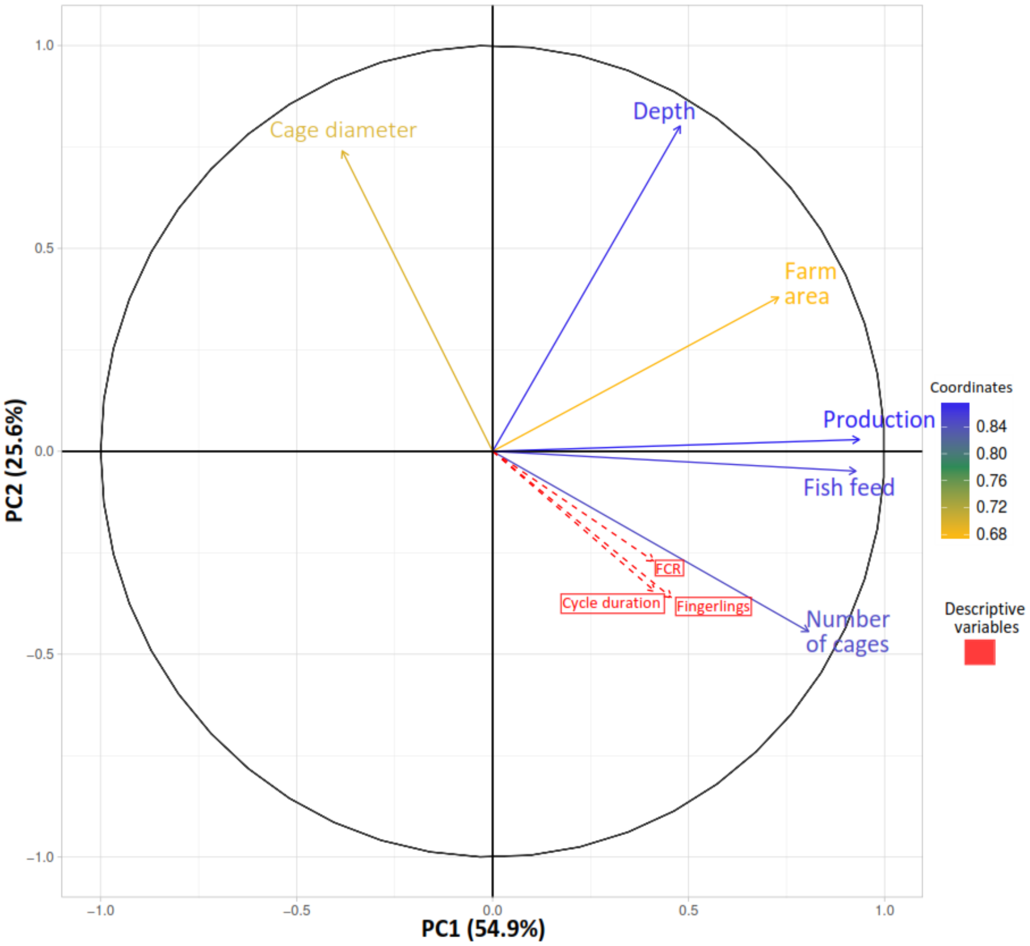


Figure 2.3 : Two-dimensional canonical graph of the variable factorial map (correlation circle of the Principal Component Analysis). PC1 and PC2 are the principal components, and "%" is the percentage of total variation in the sample explained. Direction (more responsible for PC1 (horizontal) or for PC2 (vertical)), length (nearest to the edge of the correlation circle) and colors (yellow = weaker correlation (far from the edge of circle), blue = stronger correlation (near the edge of circle)) reflect the correlations between active variables and principal components.

The Spearman coefficient "rho" demonstrated significant positive correlations between quantity of fish feed and annual production ($\text{rho} = 0.95, p = 2.17\ e^{-9}$), FCR ($\text{rho} = 0.64, p = 0.004$) and the number of cages ($\text{rho} = 0.57, p = 0.01$). The number of cages had a significant positive correlation with annual production ($\text{rho} = 0.53, p = 0.02$), fish feed and FCR ($\text{rho} = 0.57, p = 0.01$, for both) and the number of fingerlings ($\text{rho} = 0.61, p = 0.007$). Water column depth had a significant positive correlation with farm area ($\text{rho} =$

$0.65, p = 0.003$) and was weakly or negatively correlated with the other characteristics. Cage diameter had a significant negative correlation with the number of cages ($\text{rho} = -0.66, p = 0.002$) and the number of fingerlings ($\text{rho} = 0.45, p = 0.04$) but a weak negative correlation with the other characteristics (Figure 2.4).

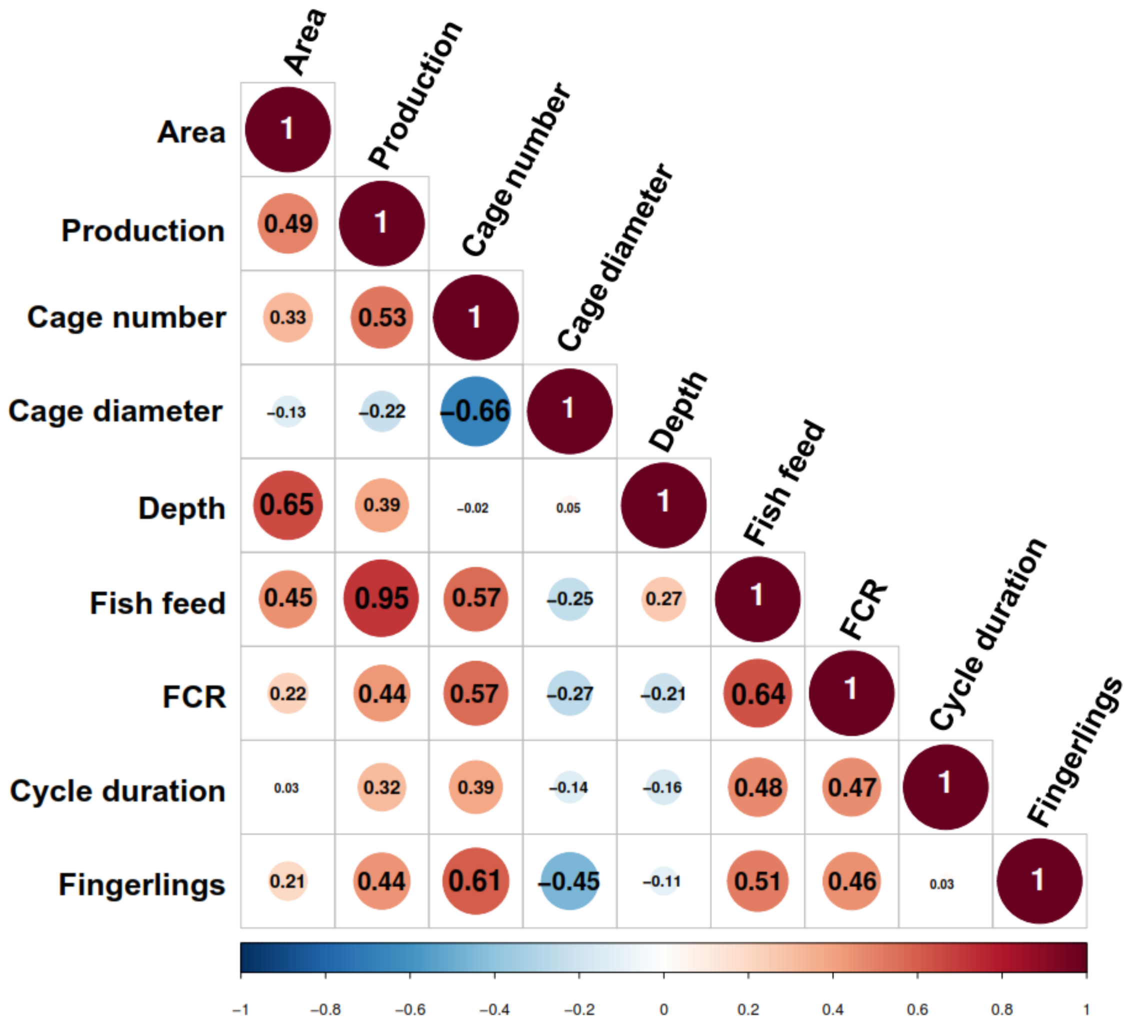
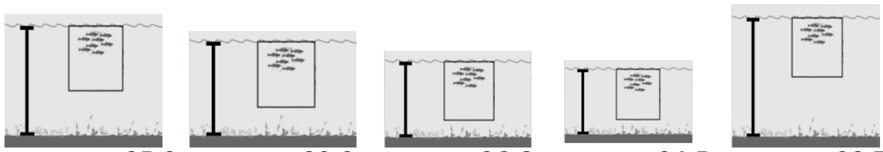
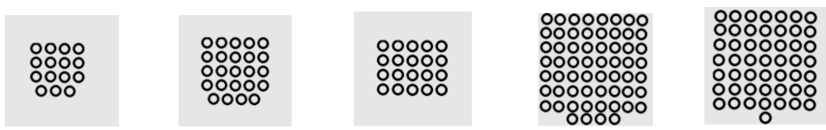
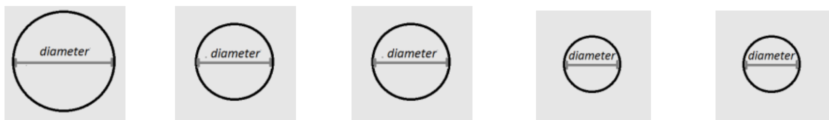
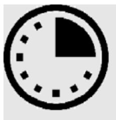
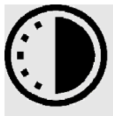


Figure 2.4 : Spearman rank correlation coefficient "rho" of nine technical aspects of Tunisian aquaculture farms (FCR= feed-conversion ratio). Circle diameters are proportional to the strength of correlation.

The final typology of the HCPC classified farms into five groups. The variables most clearly distinguishing them was water column depth, annual production and FCR (directly related to the quantity of fish feed consumed) (Figure 2.5). Farms in G1 (four farms), G2 (four farms) and G5 (three farms) had a deeper mean water column depth (35.0, 32.0 and 38.7 m, respectively) and larger mean area (49.0, 61.1 and 69.2 ha, respectively) than farms in G3 (five farms) and G4 (two farms) (mean water column depth of 26.6 and 24.5 m, respectively, and mean area of 32.4 and 45.0 ha, respectively) (Table 2.1). Farms in G4 and G5 had higher mean annual production (1,550 and 2,150 t, respectively) and more mean cages (60 and 51 cages, respectively) than farms in G1, G2 and G3 (mean annual production of 1,150, 1,125 and 752 t, respectively, and 15, 24 and 20 mean cages, respectively) (Table 2.1). Farms in G1 and G3 had the lowest mean FCR (1.8 and 1.7, respectively), which implies that they used fish feed more efficiently (means of only 1,988 and 1,261 t, respectively) and had fewer fingerlings. Farms in the other three groups (G2, G4 and G5) had higher mean FCRs (2.2, 2.1 and 2.0, respectively), which is related to the large mean quantities of fish feed required (2,403, 5,930 and 4,176 t, respectively) and the larger mean number of fingerlings. Farms in G1 and G4 were on opposite ends of the spectrum for water column depth, annual production and FCR, as were farms in G3 and G5 (Figure 2.5).

Table 2.1 : Means and coefficients of variation (CV) of technical characteristics of Tunisian aquaculture farms based on Hierarchical Clustering on Principal Components. G1 (four farms with deep water, low production, and low feed-conversion ratio (FCR)), G2 (four farms with deep water, low production, and high FCR), G3 (five farms with shallow water, low production, and low FCR), G4 (two farms with shallow water, high production, and high FCR), G5 (three farms with very deep water, very high production, and high FCR)

	G1	G2	G3	G4	G5
Annual production					
Mean (t)	1,150.0	1,125.0	752.0	1,550.0	2,150.0
CV	16.7%	22.2%	34.8%	13.7%	18.5%
FCR					
Mean	1.8	2.2	1.7	2.1	2.0
CV	3.3%	11.1%	13.3%	13.5%	7.8%
Depth					
Mean (m)	35.0	32.0	26.6	24.5	38.7
CV	10.2%	12.8%	31.0%	2.9%	3.0%
Area					
Mean (ha)	49.0	61.4	32.4	45.0	69.2
CV	16.8%	33.7%	35.5%	0.0%	30.5%
Number of cages					
Mean	15.0	24.0	20.0	60.0	51.0
CV	25.5%	27.2%	28.3%	0.0%	56.2%
Cage diameter					
Mean (m)	29.0	24.3	23.3	22.1	22.0
CV	0.0%	6.2%	6.7%	0.6%	0.0%

Amount of fish feed required					
Mean (t)	1,988.6	2,403.3	1,261.3	5,930.0	4,176.2
CV	18.0%	32.7%	37.3%	27.7%	20.8%
Number of fingerlings					
Mean (10^3 individuals)	2,137.5	4,011.2	2,314.0	5,930.0	3,827.0
CV	43.1%	37.6%	54.1%	14.5%	31.4%
Production cycle duration					
Mean (month)	12.0	14.5	13.2	15.0	14.3
CV	15.2%	11.9%	6.3%	0.0%	16.1%

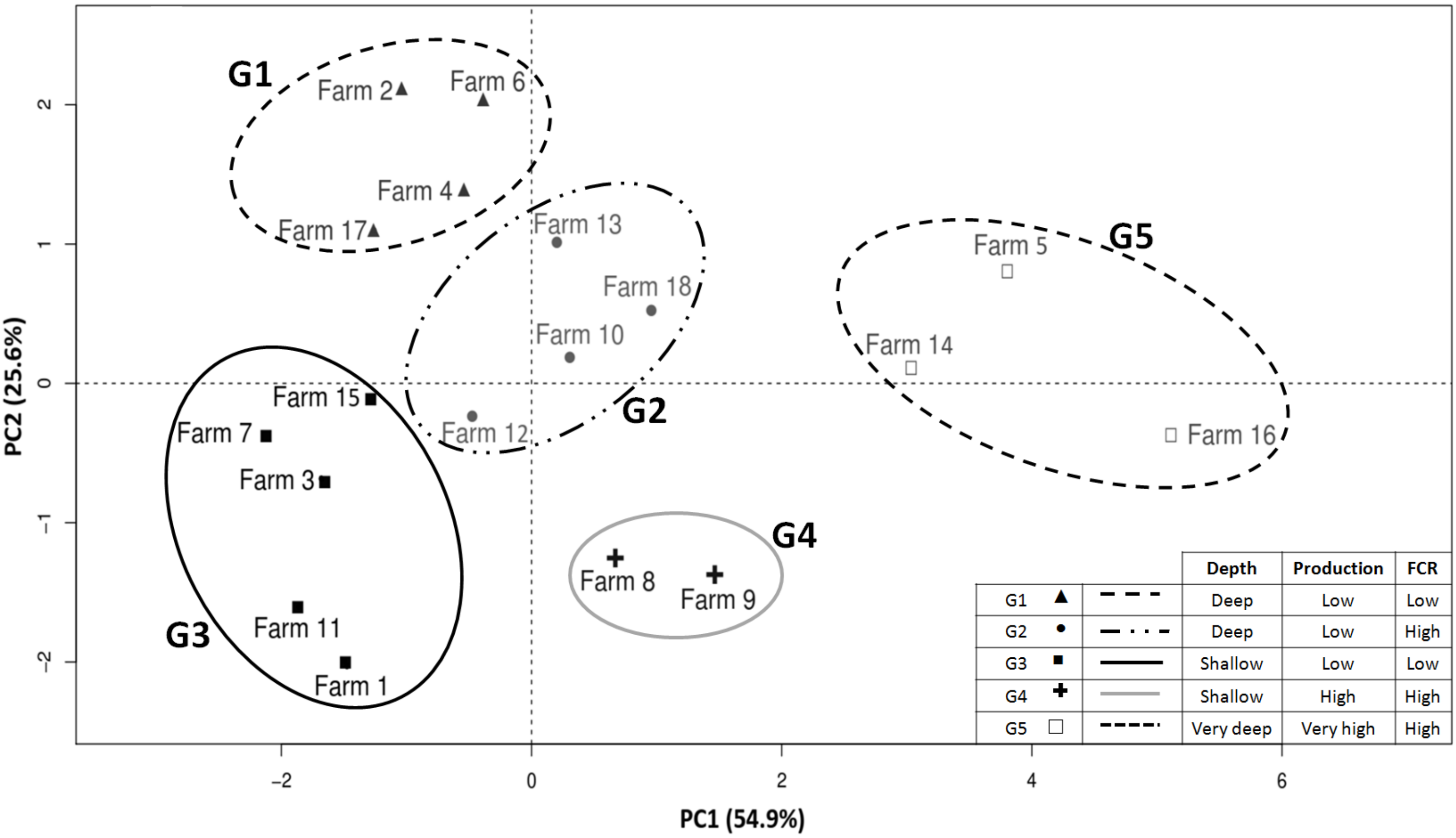


Figure 2.5 : Classification of individual farms based on Principal Component Analysis and Hierarchical Clustering on Principal Components. Axis represent scores on the PCs for variables included in the PCA. The farms were classified into five groups based on depth production and feed-conversion ratio (FCR). PC principal component.

2.2.3.2. LCA results

Mean acidification potential was higher for farms in G2 and G4 than for farms in the other groups (Table 2.2). Despite technical differences among groups, no significant difference in mean acidification was observed between farms in G2 and G4, G1 and G3 or G3 and G5. Fish feed production contributed most to mean acidification (78% for G1, 77% for G5 and 72% for the other groups), followed by fingerling production (10% for G1, 4% for G5 and 14-17% for the other groups) (Figure 2.6A).

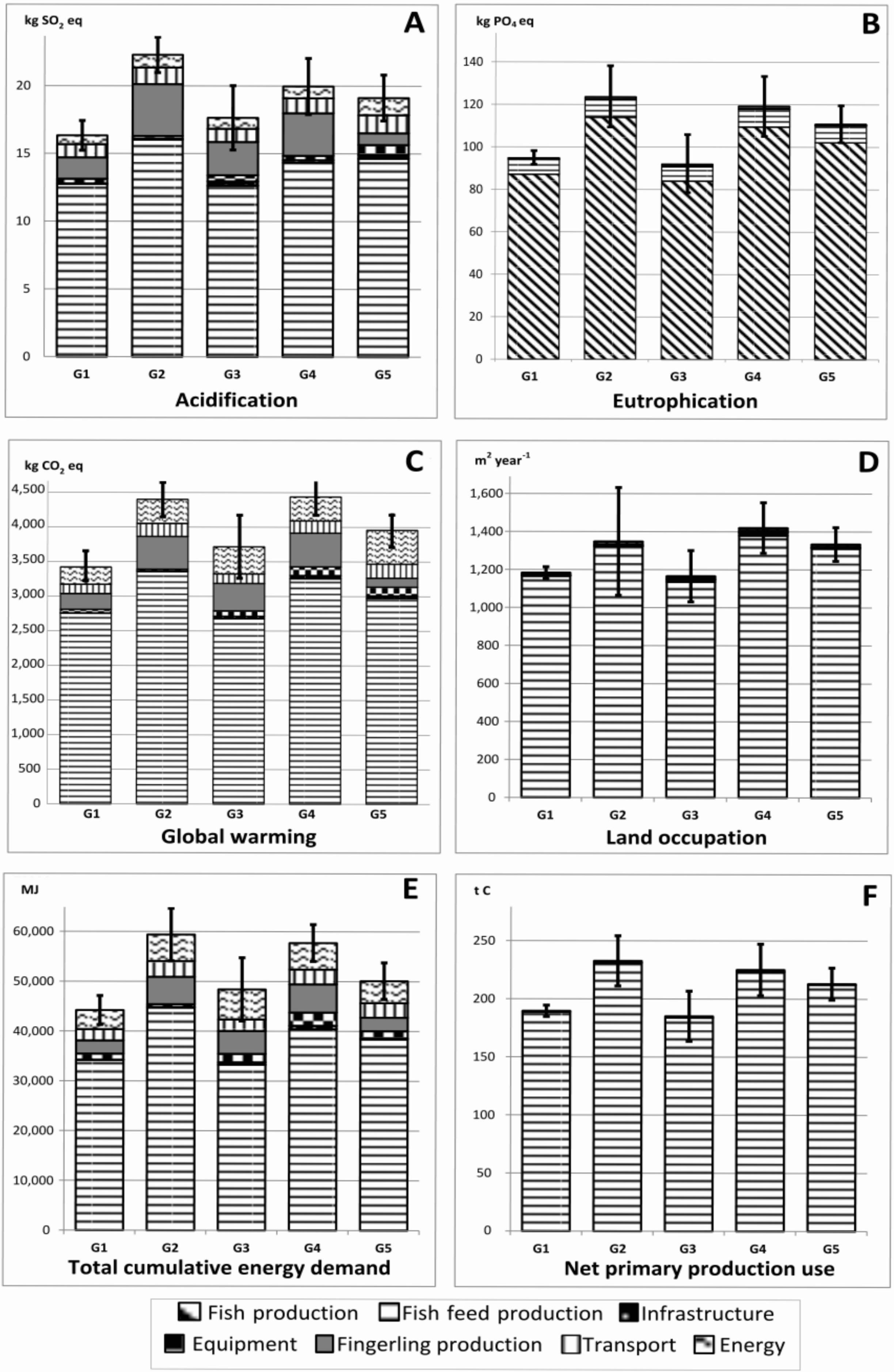
Mean eutrophication potential was lower for farms in G3 and G1 than farms in G2, G4 and G5 (Table 2.2). No significant difference in mean eutrophication was observed between farms in G2 and G4, G2 and G5, G1 and G3, G1 and G4, G4 and G5 or G4 and G3 (Table 2.3). Fish production contributed most to mean eutrophication (91%), followed by fish feed production (8%) (Figure 2.6B).

Mean global warming potential was higher for farms in G2 and G4 than farms in G1, G3 and G5 (Table 2.2). No significant difference in mean global warming was observed between farms in G1 and G3, G2 and G4, G5 and G2 or G5 and G3 (Table 2.3). Fish feed production contributed most to mean global warming (80% for G1 farms and 71-75% for the other groups), followed by fingerling production (7% for G1, 3% for G5 and 11% for G2, G3 and G4) (Figure 2.6C).

Mean land occupation was lowest for farms in G3 and highest for farms in G4 (Table 2.2). The difference in mean land occupation was significant only between G1 and G5 and G3 and G5 (Table 2.3). Fish feed production contributed most to mean land occupation (> 97%) (Figure 2.6D).

Mean TCED was higher for farms in G2 and G4 than for farms in G5, G3 and G1 (50 (Table 2.2). No significant difference in mean TCED was observed between farms in G1 and G3, G2 and G4, or G3 and G5 (Table 2.3). Fish feed production contributed most to mean TCED (69-77%), followed by fingerling production (6-9%) (Figure 2.6E).

Mean NPPuse was higher for farms in G2 and G4 than for farms in the other groups (Table 2.2). No significant difference in mean NPPuse was observed between G1 and G3, G1 and G4, G2 and G4, G2 and G5, G3 and G4 or G4 and G5 (Table 2.3). Only fish feed production contributed to NPPuse of all groups (Figure 2.6F).


A
kg SO2 eq
0
5
10
15
20
G1
G2
G3
G4
G5
Acidification
B
kg PO4 eq
0
20
40
60
80
100
120
140
G1
G2
G3
G4
G5
Eutrophication
C
kg CO2 eq
0
500
1,000
1,500
2,000
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3,000
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4,000
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G1
G2
G3
G4
G5
Global warming
D
m2 year-1
0
200
400
600
800
1,000
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Land occupation
E
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0
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G4
G5
Total cumulative energy demand
F
t C
0
50
100
150
200
250
G1
G2
G3
G4
G5
Net primary production use
Fish production
Fish feed production
Infrastructure
Equipment
Fingerling production
Transport
Energy

Figure 2.6 : Contribution of fish farm production phases to mean impacts of producing one ton of fish. Error bars represent one standard deviation (i.e. squared deviation). G1 (four farms with deep water, low production, and low feed-conversion ratio (FCR)), G2 (four farms with deep water, low production, and high FCR), G3 (five farms with shallow water, low production, and low FCR), G4 (two farms with shallow water, high production, and high FCR), G5 (three farms with very deep water, very high production, and high FCR).

2.2.3.3. Correlation and variability

FCR had strong and significant positive correlation with all impacts, especially eutrophication ($\text{rho} = 0.99, p = 4.18e^{-16}$) and NPPuse ($\text{rho} = 0.97, p = 3.69e^{-11}$). The number of cages had a significant positive correlation with acidification ($\text{rho} = 0.59, p = 0.01$), eutrophication ($\text{rho} = 0.57, p = 0.01$), global warming ($\text{rho} = 0.58, p = 0.01$) and TCED ($\text{rho} = 0.60, p = 0.008$). Annual production had a significant positive correlation with eutrophication ($\text{rho} = 0.47, p = 0.04$) and land occupation ($\text{rho} = 0.46, p = 0.04$). The quantity of fish feed required and cycle duration had a significant positive correlation with eutrophication ($\text{rho} = 0.67, p = 0.002$ for fish feed and $\text{rho} = 0.50, p = 0.03$ for cycle duration), land occupation ($\text{rho} = 0.62, p = 0.006$ for fish feed and $\text{rho} = 0.52, p = 0.02$ for cycle duration), and NPPuse ($\text{rho} = 0.61, p = 0.007$ for fish feed and $\text{rho} = 0.49, p = 0.03$ for cycle duration). Fingerlings had a significant positive correlation with acidification ($\text{rho} = 0.64, p = 0.004$), global warming ($\text{rho} = 0.61, p = 0.02$) and TCED ($\text{rho} = 0.48, p = 0.04$). Cage diameter and water column depth had a strong and significant negative correlation with each impact. Farm area was weakly correlated with each impact (Figure 2.7).

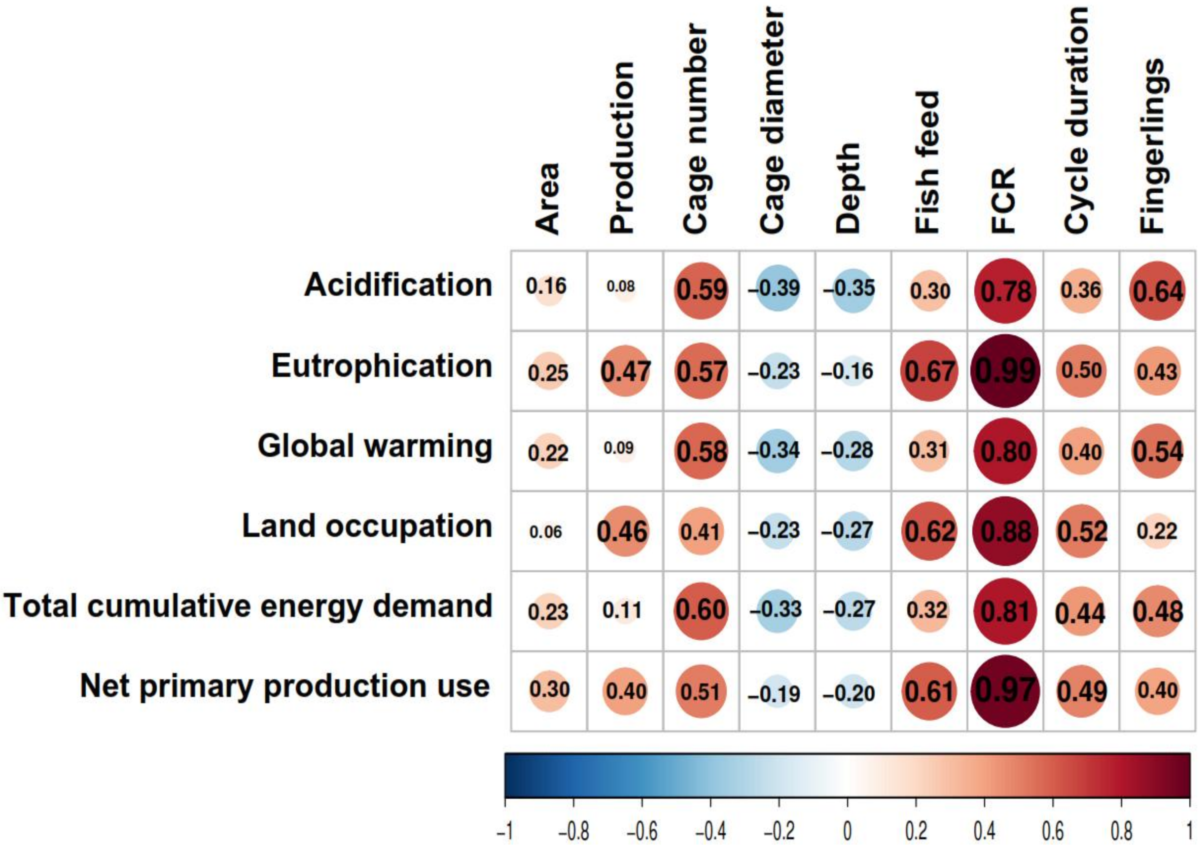

Figure 2.7 : Spearman rank correlation "rho" between the six main technical characteristics of Tunisian aquaculture farms and the six impact categories studied (FCR: feed-conversion ratio). Circle diameters are proportional to the strength of correlation. rho<0.30 weak correlation; 0.30≤rho<0.45 medium correlation; 0.45≤rho<0.60 strong correlation; rho≥0.60 =very strong correlation.

Farms in G3 and G2 had the highest CVs for all technical characteristics except cycle duration and number of cages, for which G5 had the highest CV. Farms in G4 had the lowest CV for all characteristics except FCR (for which they had the highest CV), cage diameter and quantity of fish feed required (Table 2.1). Farms in G1 had the lowest CV for all impacts except acidification and global warming, for which farms in G2 had lower CV. Farms in G3 had the highest CV for all impacts except for land occupation, for which farms in G2 had the highest CV (Table 2.2).

Table 2.2 : Environmental impacts and their coefficients of variation (CV) per ton of fish produced in Tunisian aquaculture farms: G1(four farms with deep water, low production, and low feed-conversion ratio (FCR)), G2 (four farms with deep water, low production, and high FCR), G3 (five farms with shallow water, low production, and low FCR), G4 (two farms with shallow water, high production, and high FCR), G5 (three farms with very deep water, very high production, and high FCR).

Impact	G1	G2	G3	G4	G5
Acidification					
Mean (kg SO_2 eq)	16	22	18	20	19
CV	7%	6%	13%	10%	9%
Eutrophication					
Mean (kg PO_4 eq)	95	124	92	119	111
CV	4%	13%	16%	13%	9%
Global warming					
Mean (kg CO_2 eq)	3,421	4,400	3,716	4,437	3,957
CV	7%	6%	13%	6%	6%
Land occupation					
Mean (m^2year)	1,184	1,349	1,167	1,421	1,335
CV	3%	21%	12%	9%	7%
Total cumulative energy demand					
Mean (MJ)	44,232	59,429	48,434	57,758	50,134
CV	7%	9%	13%	6%	7%
Net primary production use					
Mean (t C)	190	233	185	225	213
CV	3%	9%	12%	10%	6%

Table 2.3 : Significance tests between mean impacts of aquaculture farm groups for each impact category using Student's t-test. Bold values indicate significant (p) differences between groups. G1 (four farms with deep water, low production, and low feed-conversion ratio (FCR)), G2 (four farms with deep water, low production, and high FCR), G3 (five farms with shallow water, low production, and low FCR), G4 (two farms with shallow water, high production, and high FCR), G5 (three farms with very deep water, very high production, and high FCR).

Acidification

	G1	G2	G3	G4	G5
G1	1				
G2	**$8.05e^{-05}$**	1			
G3	0.1842	**0.0064**	1		
G4	**0.0005**	0.7251	**0.0102**	1	
G5	**0.0155**	**0.0029**	0.5511	**0.0084**	1

Eutrophication

	G1	G2	G3	G4	G5
G1	1				
G2	**0.0134**	1			
G3	0.6762	**0.0086**	1		
G4	0.1001	0.7451	0.0600	1	
G5	**0.0367**	0.1843	**0.0400**	0.4438	1

Global warming

	G1	G2	G3	G4	G5
G1	1				
G2	**$8.32e^{-05}$**	1			
G3	0.1741	**0.0071**	1		
G4	**0.0061**	0.6992	**0.0234**	1	
G5	**0.0237**	0.1271	0.4432	0.0547	1

Land occupation

	G1	G2	G3	G4	G5
G1	1				
G2	0.2640	1			
G3	0.7713	0.2396	1		
G4	0.0867	0.6452	**0.0500**	1	
G5	**0.0365**	0.9202	**0.0444**	0.3942	1

Total cumulative energy demand

	G1	G2	G3	G4	G5
G1	1				
G2	**0.0017**	1			
G3	0.1892	**0.0121**	1		
G4	**0.0081**	0.6191	**0.0294**	1	
G5	**0.0412**	**0.0173**	0.6002	**0.0482**	1

Net primary production use

	G1	G2	G3	G4	G5
G1	1				
G2	**0.0097**	1			
G3	0.6412	**0.0057**	1		
G4	0.1051	0.6580	0.0623	1	
G5	**0.0301**	0.1421	**0.0370**	0.4650	1

2.2.4. Discussion

Developing sustainable aquaculture to meet sustainable development goals is a priority, especially goal 2 (end hunger, achieve food security, improve nutrition and promote sustainable agriculture) and goal 12 (ensure sustainable consumption and production patterns). To this end, aquaculture farms must improve several production practices, mainly energy efficiency and feed consumption. LCA has been applied to several aquaculture systems worldwide (Chen et al., 2015; Henriksson et al., 2015; Jerbi et al., 2012; Papatryphon et al., 2004) because of its complete perspective. A general understanding of potential impacts generated by aquaculture farms is crucial to meet sustainability goals for aquaculture. The typology defined in this study was based on several technical characteristics of aquaculture using HCPC, which has never been combined with an aquaculture LCA. Combination of PCA/HCPC and LCA allowed us to assess environmental performances of each group of aquaculture farms. To our knowledge, only one LCA of fish farming in sea cages in Tunisia has been performed, and it is based on one aquaculture farm (Abdou et al., 2017b). The farm studied by Abdou et al. (2017) is included in G1 in the present study.

High FCR reflects low efficiency in input use (mainly fish feed) and consequently is associated with large quantities of inputs (e.g. crop-based ingredients and energy). This highlights the importance of adapting suitable farming and feeding practices (e.g. stock management, feed distribution, accurate ration calculation) to reduce the FCR and environmental impacts. The negative correlation between water column depth and impacts suggest that impacts of fish farms decrease as depth increases. This is the case of farms in G1. Shallow depth induces organic matter accumulation, water quality degradation and potentially proliferation of pathogens (Borja et al., 2009). Greater depths increase waste dispersion and consequently improve water quality (Cromey et al., 2002). Farms in deeper water would have higher global warming impacts because they use more fuel than farms in shallow water to reach the sites, which results in greater emissions to the air. However, distances between farms and ports in Tunisia are relatively short, thus no significant difference in impacts was observed between farms with deep water columns and farms with shallow water columns.

Farms with low impacts (G1) had fewer cages with larger diameters and shorter production cycles. In contrast, farms with high impacts (G2, G4 and G5) had smaller cages and longer production cycles. In Tunisia, cage size is directly related to stocking density per cage. Despite differences in cage size, all aquaculture farms stock the same number of fingerlings per cage; thus, stocking density is higher in smaller cages than in larger cages. Stocking density is one of the most important variables in aquaculture because it negatively influences the growth rate (Lefrançois et al., 2001; Procarione et al., 1999; Schram et al., 2006), feeding rate (Rowland et al., 2006), health and survival (Di Marco et al., 2008; Iguchi et al., 2003), fish behaviour (Kristiansen et al., 2004), feeding and production (Rowland et al., 2006). Inappropriate stocking density can compromise fish health and reduce the immune system due to poor welfare, which then has a negative influence on profitability of the aquaculture system (Di Marco et al., 2008; Huntingford et al., 2006; North et al., 2006; Turnbull et al., 2005). High stocking density was identified as a major source of stress in aquaculture studies that demonstrated the influence of stocking density on different aspects of farmed-fish welfare. Daily feed intake and growth rate decreased with high density of gilthead seabream (Canario et al., 1998; Montero et al., 1999) and seabass (Sammouth et al., 2009; Vazzana et al., 2002).

Results indicate that impact intensity in fish farms is not related to productivity but can be due to production management (e.g. feeds, energy). It is difficult to manage these aspects and obtain adequate technical efficiency when the aquaculture farm contains many cages, which results in a higher FCR and higher environmental impacts. In this study, despite high variability in technical characteristics of farming, several groups had no significant differences in impact intensities (e.g. G1 and G2, G2 and G4).

Rearing practices contributed most to eutrophication for all farm groups. This is directly related to nutrient emissions (N and P) associated with the efficiency of fish feed use. Efficient use of feed is strongly related to technical strategies of farms. High FCR results from a large amount of uneaten food, dissolved nutrients in metabolic waste, and excreted undigested food. However, the relevance of this impact category can be challenged because the calculation does not consider the ecosystem’s assimilation capacity (the nutrient mass per unit of area that the ecosystem can retain permanently) (Richardson and Qian, 1999). Due to lack of specific data, we could not consider differences between the two reared species (e.g. in FCRs, cycle duration or growth and mortality rates), which can influence impacts of each species.

Fish feed production contributed most to acidification, global warming and TCED for all farm groups. The correlation analysis indicated a strong positive correlation among these three impacts, quantity of fish feed required and the number of cages. The large contribution of fish feed is due to the inclusion of fish meal and fish oil as major ingredients. At a global scale, 46% of fish meal production and 81% of fish oil production were destined for aquaculture in 2002 (Tacon, 2005). Finding other sources of protein and lipids for fish feed is a challenge in aquaculture, and using fish feed containing wild-fish meal and oil is debated when compared to commercial fishing (Ellingsen and Aanondsen, 2006). An important way to improve the environmental performance of aquaculture is to identify alternative sources of protein and lipids (Dias et al., 2009). Fish feed production is the only contributor to land occupation and NPPuse due to the agriculture-based ingredients which require a large terrestrial area and a large amount of primary production (Mungkung et al., 2013). This suggests that replacing fish meal and fish oil with plant-based ingredients could reduce eutrophication impact and decrease dependence and pressure on wild fish stocks (Papatryphon et al., 2004). This would also decrease fish-based protein and lipid ingredients in feeds, increase FCR and provide some economic benefits (Aubin et al., 2009). However, it could possibly shift environmental impacts, increasing land occupation and, to a lesser extent, TCED (Mungkung et al., 2013).

The predominant contribution of fish feed to most impacts reflects the heavy influence of its production, from collection of raw materials up to processing, which requires large amounts of energy and resources. Fish feed is a major economic concern for all Tunisian aquaculture farms because all of it is imported; the necessary ingredients do not exist locally (DGPA 2014). A decline in fishery captures could decrease fish meal and oil production. Thus, building a feed-production facility in Tunisia would reduce environmental impacts by reducing transport distances of fish feed and ingredients (mainly fish meal and fish oil) (since they are currently imported) and by using co-products from Tunisian fisheries as ingredients. Stakeholders in Tunisia should encourage development of farms with deeper water columns and lower FCR to decrease environmental impacts.

Given the multi-criteria aspect of LCA, we estimated multiple environmental impacts associated with production of one ton of fish for different groups of aquaculture farms in Tunisia. Results obtained from the LCA are valuable to support decision-making and to identify key processes to improve the environmental performance of aquaculture and facilitate its sustainable development. The analysis could be improved by studying the uncertainty throughout the entire production cycle and by including additional impact categories to capture additional environmental, economic and/or social characteristics of aquaculture. This study can be supplemented with economic and the social analyses, which would require more farm-specific data. The current "cradle-to-farm-gate" analysis would be improved if more data were available, which would extend the boundaries of the studied system to include post-farm processes related to aquaculture and consequently consider the entire production cycle. This study could also be improved by considering potential impacts of each reared species, because they have different FCRs, growth rates, mortality rates and cycle durations. This would be possible if more specific data were available.

2.2.5. Conclusion

In this study, PCA and HCPC were used to classify and characterise 18 Tunisian aquaculture farms which follow intensive rearing practices in sea cages. An LCA was performed to assess the environmental performance of producing one ton of seabass and seabream. This typology approach is a novel method that has never been applied to seafood LCA and it captures the variability among farms because it considers several farm characteristics in the classification. The study revealed that rearing practices and fish feed were the greatest contributors to the impacts studied. FCR, which is directly influenced by feeding practices, contributed most to most impacts. Low efficiency of fish feed use emits large amounts of N and P into the environment. Based on this finding, we conclude that optimising fish feed use and production would have a positive influence on overall environmental performance, especially because protein and lipids required by cultured fish is principally provided by fish meal and fish oil. It is thus imperative to optimise feed formulation and follow better feeding strategies to decrease the FCR and improve the environmental performance of aquaculture farms. Water column depth, FCR and cage size had the greatest influence on impacts generated by aquaculture farms. Controlling these characteristics reflect the degree of control over management parameters and the technical expertise of farm managers and workers. Stakeholders should encourage development of environmentally-conscious aquaculture farms to ensure long-term sustainability of the sector. They should grant licenses for farms in deeper water with larger cages and encourage them to improve their FCRs. Cage size reflects the stocking density, which can directly affect the welfare of fish and consequently farm performance. Decision makers must also enforce aquaculture regulations to protect the marine environment. This study can be improved by considering differences between reared species and studying uncertainty throughout the entire production cycle to provide more accurate and reliable results.

2.3. Manuscrit B "Environmental assessment of seabass (*Dicentrarchus labrax*) and seabream (*Sparus aurata*) farming from a life cycle perspective: A case study of a Tunisian aquaculture farm"

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Abstract

Life Cycle Assessment (LCA) was applied to assess potential environmental impacts generated by production of 1 ton of European seabass (*Dicentrarchus labrax*) and gilthead seabream (*Sparus aurata*) on a sea-cage aquaculture farm in Tunisia. The studied farm produces 2 100 tons of fish per year. Impact categories included in the current study were acidification, eutrophication, global warming, land occupation, total cumulative energy demand and Net Primary Production Use (NPPuse). In addition, a refinement of "sea use" impact category was proposed to assess impacts of aquaculture on the area of sea required and seabed degradation. Calculations were performed using the software SimaPro® 8.0, and the database ecoinvent 3.0 was used for background data. Uncertainty analysis was performed using Monte-Carlo simulations. Results of this study indicate that seabass rearing has lower mean impact than seabream rearing for all the impact categories considered. However, no significant differences were observed in all the impact categories except the global warming. Fish feed is the main contributor to most of the impacts studied, which is directly related to production of fish meal and oil as feed ingredients and the large amounts of nitrogen and phosphorus released into the environment. Management decisions aiming to optimize production and use of fish feed may have a positive impact on the environmental performance of the farm. It is essential to optimize diet formulation and to follow better feeding strategies and farming practices (e.g. stock management, feed distribution, accurate ration calculation) to lower feed-conversion ratios and consequently improve the environmental performance of aquaculture farms. LCA is a valuable tool for assessing decisions for improving environmental sustainability of aquaculture because it performs overall impact assessment and helps identify main areas for improvement.

Keywords: Marine aquaculture, Life Cycle Assessment (LCA), MERAMOD®, Sea use, Tunisia.

2.3.1. Introduction

World demand for seafood increased from 9.9 kg per capita in the 1960s to 19.7 kg in 2013, with preliminary estimates exceeding 20 kg per capita in 2015 (FAO, 2016). However, this increase in demand is no longer sustained by fishing, which has remained stable for more than 10 years, whereas aquaculture production increased at an average rate of 23.5% from 2009-2014 (FAO, 2016). At present, approximately 44% of consumed fish are farmed, and this percentage is predicted to reach 52% by 2025 (FAO, 2016). The Mediterranean aquaculture industry has grown rapidly since its inception, facilitated by the geography and chemical and physical conditions in the zone (FAO, 2008).

Located on the southern coast of the Mediterranean and in northern Africa, Tunisia has more than 1300 km of coastline, and fisheries and aquaculture play a crucial socio-economic role. Over the last 25 years, aquaculture has expanded in Tunisia's coastal zone and is becoming an increasingly important industry; accounting for almost 3% of Tunisia's total fish production, which itself contributes nearly 3% of gross domestic products (GDP). Aquacultural activity is mainly marine-oriented, with annual production of almost 10 000 tons in 2014, according to Fisheries and Aquaculture Department statistics (DGPA, 2014). There are 24 offshore aquaculture farms in Tunisia's exclusive economic zone (EEZ), most of which are located on the country's eastern side. The reared species with the highest economic value are European seabass (*Dicentrarchus labrax*) and gilthead seabream (*Sparus* *aurata*), for which market prices per kg range from 9-12 TND (Tunisian dinar) (3.66-4.88€) and 8-10 TND (3.25-4.07€), respectively. In light of current social, economic and environmental contexts, it is necessary for aquaculture production systems in Tunisia to develop sustainably. On a Mediterranean scale, Tunisian fish farming is considered a small industry with a high potential for growth. It was ranked the 8th Mediterranean reared fish producer in 2013, and its production represents almost 1% of total aquaculture production in the Mediterranean Sea (FAO, 2016). Production varies considerably among farms: large farms produce more than 2 600 tons per year, while small farms produce approximately 600 tons per year. Difference in production among farms is a direct result of the number of cages and the aquacultural techniques they adopt.

It is clear that long-term sustainability of the industry is a major concern from an environmental and ecological viewpoint. Aquaculture carries the risk of negative environmental impacts because of its close relation with the immediate environment. These risks can occur from the use of natural resources (Naylor et al., 2000) and pollutant and waste emissions (Read and Fernandes, 2003), along with specific local impacts such as disease transmission, dispersal of non-native species and release of antibiotics and pharmaceuticals into the water (Pelletier and Tyedmers, 2008). Aquaculture can also influence ecosystems and biodiversity. For example, biodeposition from fish farms into the benthic environment increases organic loads and changes sediment characteristics (Klaoudatos et al., 2006; Neofitou et al., 2010). Benthic assemblages near aquaculture farms exhibit symptoms of disturbance and a decrease in biodiversity (Karakassis, 2000). In addition to local impacts, fish farming causes indirect impacts via production of fish-feed ingredients, energy use (e.g. fuel, electricity) and construction of infrastructure and buildings (Pelletier and Tyedmers, 2008; Thrane, 2004). Due to increasing impacts of aquacultural activity at local and global scales, it is necessary to develop a science-based integrative approach to impact assessment to better understand environmental consequences of aquaculture and ensure its sustainability (Samuel-Fitwi et al., 2012).

Life Cycle Assessment (LCA) is a robust, standardized analytical method (ISO 14040) (ISO, 2006a, 2006b) designed principally to estimate potential environmental impacts associated with a product or a service, including the resources required and pollutants emitted throughout all stages of its life cycle, "from cradle to grave", i.e. from raw material extraction, construction and use, to waste management and recycling or disposal (Guinée et al., 2002). A characterization model converts each substance emitted or consumed into a potential environmental impact and assigns it to one or more impact categories to which it may contribute (Aubin et al., 2009). This method consists of four interrelated phases: goal and scope definition, life cycle inventory (LCI) analysis, impact assessment and interpretation of results (ISO, 2006b).

Most "classic" environmental studies of seafood production focus solely on local impacts of aquaculture farms and ignore many other impacts related to several industrial processes involved in fish farming (e.g., feed production, extraction of raw materials, construction and use of infrastructure and equipment) (Farmaki et al., 2014; Luna et al., 2013; Ottinger et al., 2016; Sánchez-García et al., 2014). The scientific literature on LCA of aquaculture continues to grow, increasing from only 2 publications in 2004 to more than 23 in 2012 (Aubin, 2013). Performing LCA of seafood production provides new insights into its environmental impacts (Ziegler et al., 2016). In the northern Mediterranean, LCA was used to assess impacts of French and Greek aquaculture farms (Aubin et al., 2009). In the southern Mediterranean, however, LCA has been applied to only one aquaculture case study: an intensive land-based rearing system (Jerbi et al., 2012). In this context, the current study is an initial attempt to explore and estimate environmental impacts of seabass and seabream sea-cage aquaculture farms the southern Mediterranean (Tunisia) to identify hotspots that should be enhanced to improve environmental sustainability.

2.3.2. Materials and methods

2.3.2.1. Studied system

The studied system is an offshore sea-cage aquaculture farm (125 ha) located on the eastern coast of Tunisia that specializes in rearing European seabass (630 t year $^{-1}$) and gilthead seabream (1470 t year $^{-1}$) with a total production of 2 100 tons per year (630 t year $^{-1}$ of seabass, and 1470 t year $^{-1}$ of seabream). Fingerlings of both species (mean individual weight of 3-5 g) are imported from a hatchery in southern France. Seabass grow for approximately 18 months to reach a commercial weight of 350-400 g, while seabream grow for 10 months to reach a commercial weight of 270 g. The aquaculture farm under study consists of 36 circular net-cages (29 with a 22 m diameter and 5 with a 29 m diameter). Mean water depth under the cages is 32 m with a sandy substrate. The farm is equipped with 5 boats (for feeding and fishing) and two land-based facilities, one for administration and the other to stock feed and materials. The aquaculture farm is one of the five most productive aquaculture farms in Tunisia and is ranked third in the number of sea cages. The water depth under the farm is considerably shallower than that under most other Tunisian farms (Appendix 2.3).

All fish feed used on the farm is imported from Italy. It consists of two types: one for seabream (46% protein, 16% lipids and 3.5% fiber) and the other, for seabass, with less protein (40%), more lipids (24%) and the same amounts of fiber (3.5%) (Table 2.4). The fish feed is mixed with a vitamin premix before being distributed; therefore, we consider it part of the fish feed composition. Vitamin premix protects reared fish from viral and bacterial diseases by stimulating the immune system.

Feed-conversion ratio (FCR), calculated by dividing the total feed intake divided by net production of a species, is considered the main indicator of efficiency of a feeding strategy. FCRs provided by the farm manager (later confirmed by calculations) were 1.85 for seabream and 1.88 for seabass. These FCRs do not differ from those reported for most Tunisian farms.

Table 2.4 : Ingredients and chemical composition of fish feeds used on the farm.

	Seabream feed	Seabass feed	Origin
Ingredients (g/kg)			
Fish meal	380	420	Peru
Fish oil	280	240	Peru
Soybean meal	170	150	Brazil
Grain maize meal	0	50	France
Wheat	50	35	France
Wheat gluten meal	50	35	France
Sunflower meal	10	10	France
Pea meal	35	35	France
Rapeseed meal	10	10	France
Vitamin and mineral premix	15	15	
Chemical composition (%)			
Crude protein	46.0	40.0	
Crude fat	16.0	24.0	
Crude fiber	3.5	3.5	
Ash	6.5	6.5	
Phosphorus	0.9	0.9	
Sodium	0.2	0.3	
Calcium	0.8	1.0	
Gross energy (MJ/kg)	16.1	17.4	

2.3.2.2. LCA

2.3.2.2.1. Goal and scope

The main goal of the current study is to estimate environmental impacts of rearing seabass and seabream on a sea-cage aquaculture farm. The system assessed includes a wide variety of fish-production processes. System boundaries include inputs (i.e. fish feed and its production, fingerlings and their importation, energy requirements, infrastructure and equipment) and outputs (e.g. fish produced, nitrogen (N) and phosphorus (P) emissions in solid and dissolved forms). Several post-farm production stages (e.g. sorting and packaging, commercialization, use and disposal at the end of life) were excluded due to lack of reliable data (Figure 2.8). Because the final product is 1 ton of fish (functional unit) at the fish farm gate, the current study is a "cradle-to-farm-gate" assessment.

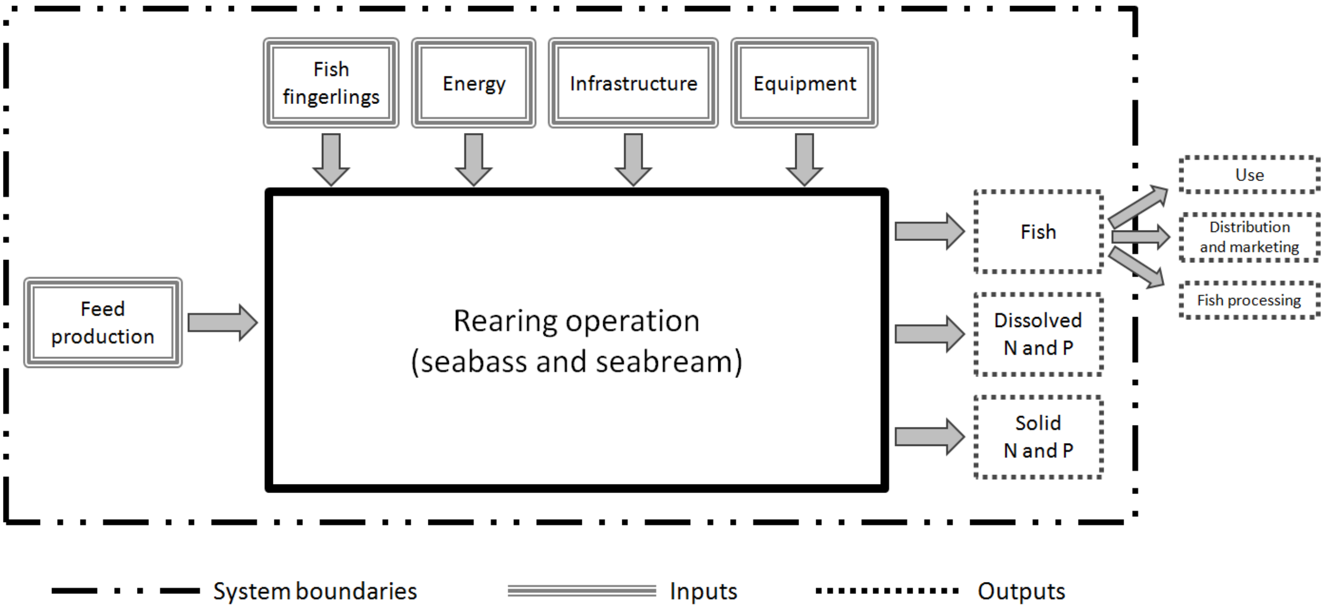


Figure 2.8 : Diagram representing stages of the fish production system studied

2.3.2.2.2. Life cycle inventory

LCI data for one year of production were obtained from farm records and interviews with managers and workers of the fish farm. Several field trips were taken (January, March and May 2015) to obtain more detailed information to validate the previously collected data and complete the LCI. Data on ingredient composition of fish feed were based on commercial labels and were completed with full percentage-composition analyses performed by the central laboratory for cattle-feed analysis in Tunisia (centesimal analysis). This analysis provided the approximate diet formulation (i.e. the percentages of each ingredient in 1 kg of fish feed) (Table 1). Data were validated using detailed reports provided by the feed-mill manager and a nutritionist. The fish meal and fish oil in the fish feed were produced from Peruvian anchovy (*Engraulis ringens*). The Peruvin industrial anchoveta fishery is one of the most fuel-efficient fisheries in the world on a per landed tonnes basis (Fréon et al., 2014).

The ecoinvent 3.0 database was used for all background data. Ecoinvent 3.0 processes used in the study were equivalent to ecoinvent 2.2 processes.

For outputs, nutrient emissions associated with the fish growth phase were predicted using a mass-balance model (Cho and Kaushik, 1990). Solid and dissolved fractions of the N and P emitted were based on the difference between the amounts of nutrients provided to the fish and the amounts assimilated in fish weight gain. The solid and dissolved forms were distinguished by considering nutrient digestibility of the feed, fish body composition and the estimated amount of uneaten feed. N and P entered the system in fingerlings and fish feed and left the system in live fish, dead fish, uneaten feed and fish emissions during the growing phase. This modeling approach and its equations were previously adapted and validated for several fish species (Bureau et al., 2003; Kaushik, 1998; Lemarié et al., 1998; Mallekh et al., 1999) and were also used in previous LCI of fish-production systems (Aubin, 2014; Aubin et al., 2009, 2006; Jerbi et al., 2012; Mungkung et al., 2013; Avadí et al., 2015). In addition, we estimated theoretical oxygen demand (ThOD), which is the stoichiometric amount of oxygen required to oxidize emitted organic compounds (uneaten feed and fish feces), based on the chemical oxygen demand of protein, carbohydrates, lipids, ash and fiber (Kim et al., 2000). Inventory data were collected through surveys in the studied fish farm. Authors had access to the fish farm historical datasets from which detailed data were obtained. Moreover, several data were obtained from multiple confidential and anonymous sources and were used to validate the inventory. Several assumptions, based on expert opinions, were made for data manipulation and values refinement. It was assumed that importation of fish feed, feed ingredients and equipments were transported by transoceanic ship from the closest trading ports, or by lorries using the shortest driving itinerary to the production facility. Moreover, it was assumed that no chemicals were used during the fish production phase. Detailed inventory process and values used can be found in Supplementary material (Appendix 2.2).

Deposition of solid matter from the fish farm on the seabed was predicted using the MERAMOD® model v.1.6. MERAMOD, a particle-tracking model derived from the DEPOMOD® model (Cromey et al., 2002), contains four modules: (i) grid generation, to create a grid containing information about bathymetry and cage layouts; (ii) particle tracking, to predict initial deposition of particles based on wastage rate of fish feed, feces production and local hydrodynamics; (iii) resuspension, to redistribute particles according to the current near the bottom to predict the net solids accumulated within each cell of the grid; and (iv) benthic community response, which is estimated from quantitative relations between benthic communities and accumulated solids (Cromey et al., 2012).

In this study, we didn't consider resuspension and benthic community response modules due to lack of reliable data concerning current circulation and benthic composition in the region. To improve MERAMOD predictions, fish production was divided into four subsystems (reticules). For each reticule, total grid size is 285 m × 285 m, and each cell covers an area of 9 m^2. Cage characteristics (e.g. dimensions, orientations, distance between cages) were determined and represented in the model. Water depth under the cages was set to 32 m, and horizontal current velocity was set to 10.5 $cm.s^{-1}$, the annual mean velocity in the farm area. Water content in the food was set at a default value of 9%, with a digestibility of 70%. These values, based on technical data provided by feed manufacturers, are recommended in the absence of specific estimates (Cromey et al., 2002). Food wastage was estimated as 5% of the total food distributed. Dispersion coefficients quantify horizontal (k_x, k_y) and vertical (k_z) dispersion in the water body. Since site-specific coefficients were unavailable, we used values recommended by Gillibrand and Turrell (1997) (k_x=0.1 m^2 s^{-1}, k_y=0.1 m^2 s^{-1}, k_z=0.001 m^2 s^{-1}). The remaining parameters were set at default values suggested by Cromey et al. (2002) (i.e. food-settling velocity (9.5 cm s^{-1}), fecal settling velocity (3.5 cm s^{-1}) and trajectory-evaluation accuracy (60 s)). Since rates of farm-derived solid matter (kg m^{-2} $year^{-1}$) vary, the degree of impact was divided into three categories based on rates of solid-matter deposition (Cromey et al., 2012):

- lightly impacted: deposition of solid matter < 3 kg m^{-2} $year^{-1}$
- moderately impacted: deposition of solid matter = 3-7 kg m^{-2} $year^{-1}$
- heavily impacted: deposition of solid matter > 7 kg m^{-2} $year^{-1}$

2.3.2.2.3. Life cycle impact assessment

Next step LCI data (resource use and compound emissions) were aggregated into impact categories and calculated per ton of fish produced. Environmental impact assessment followed the CML2 baseline 2000 method using SimaPro 8.0. Impact categories were based on previous guidelines in aquaculture LCA (Aubin et al., 2009; Henriksson et al., 2012; Jerbi et al., 2012; Mungkung et al., 2013; Pelletier et al., 2007):

- Acidification represents negative acidic effects on water and soil; it is expressed in kg SO_2 equivalent (eq) and was based on the mean characterization factor for European acidification potential (Huijbregts, 1999).
- Eutrophication represents negative impacts of large amounts of nutrients in the environment; is defined as an increase in primary and secondary production resulting from the enrichment of the ecosystem with nutrient and organic matter (Nixon, 1995). It is expressed in kg PO_4 eq and was calculated using factors found in Guinée et al. (2002), including estimates of ThOD of solid wastes using the mass-balance method.
- Global warming represents potential impact of gaseous emissions on heat-radiation absorption in the atmosphere, which causes climate change and is considered a major threat to global ecosystems (Rockström et al., 2009). This impact category assesses impact of greenhouse gas emissions on the atmosphere's ability to absorb infrared radiation. It is expressed in kg CO_2 eq and was calculated as global warming potential over a 100-year time horizon (GWP_{100}) according to the UN Intergovernmental Panel on Climate Change (IPCC, 2014).
- Land occupation represents the terrestrial ground area used and is expressed in m^2 year.
- Net Primary Production use (NPPuse) represents the amount of carbon (C) necessary for fish production as a biotic resource and is expressed in kg of C (Papatryphon et al., 2004). It combines primary production from terrestrial and marine sources to obtain an overall NPPuse impact. For ingredients of terrestrial origin, we used the C content of crops (g C per kg of crop dry matter (Tyedmers, 2000)). For fishery-derived ingredients, we calculated the C content based on Pauly et al. (1995), who used wet weights (M) and trophic levels of marine organisms (T) to calculate NPP: $NPP=(M\ 9^{-1})\ 10^{(T-1)}$
- Total cumulative energy demand (TCED) represents the amount of energy (e.g. fossil fuels, wood, electricity) required for fish production; it is expressed in MJ and was calculated according to the lower heating values available in SimaPro (Pré Consultants, 1997).
- Sea use represents the sea area required for fish production; it was derived from the land occupation impact category and is expressed in m^2 year (Langlois et al., 2014). It

considers the sea area necessary for aquaculture and the seabed area impacted to produce its inputs. To calculate sea use, we used characterization factors for seabed destruction and transformation of Langlois et al. (2015). In this study, we further expanded the sea use impact category to include sea area occupied by the farm and swept by fishing vessels, and the seabed area impacted by farm activities. The seabed area under the cages was based on MERAMOD predictions. The seabed area impacted by fishing was represented as the area swept by fishing equipment (necessary for production of fish meal and fish oil). Combining the MERAMOD model with LCA to estimate impacts of aquaculture is one novel approach of this study.

2.3.2.3. Uncertainty analysis

It is especially difficult to define LCIs for aquaculture because practices differ among farms as a function of farmers' knowledge. As a consequence, uncertainty is high and may call the validity and robustness of LCA results into question. It is necessary to consider these uncertainties to better assess the accuracy of LCI and LCA calculations. Uncertainties in LCA are associated with input data in the LCI (e.g. data variability, incorrect estimates, outdated or unrepresentative data, measurement errors), modeling assumptions, characterization and/or normalization factors (Finnveden et al., 2009; Heijungs and Huijbregts, 1999; Henriksson et al., 2013).

In the current study, data for unit processes (i.e. the smallest element considered in LCI analysis, for which input and output data are quantified (ISO (The International Organization for Standardization), 2006b)) were based on a horizontal averaging protocol (Henriksson et al., 2013) developed from a Numerical Unit Spread Assessment Pedigree. The protocol assesses data quality by considering inherent uncertainties (related to measurement errors and inaccuracies), spread among data (variability around an average resulting from horizontal averaging) and unrepresentativeness of data (resulting from the level of representativeness) (Henriksson et al., 2013). We performed 100 Monte-Carlo simulations, the method most commonly applied in LCA uncertainty analysis (Avadí and Fréon, 2013a). In Monte-Carlo analysis, values (of inputs (e.g. fish feed, fingerlings, energy, infrastructure and equipment) and outputs (N and P emissions in solid and dissolved forms)) are dependently sampled from unit process distributions for a fixed number of iterations and then aggregated into LCA results to produce a range of possible results. The uncertainty ranges calculated estimate the uncertainty in impacts generated by producing 1 ton of fish and are useful when comparing results to those of similar farms.

2.3.3. Results

2.3.3.1. Comparing environmental impacts of the two species

Mean acidification potential is higher for seabream (21 kg SO_2 eq ton^{-1}) than for seabass (18 kg SO_2 eq ton^{-1})(Table 2.5), but uncertainty analysis suggested that the difference is not significant ($p = 0.44$) (Figure 2.9). Acidification potential is dominated by feed production (70% and 80% for seabream and seabass, respectively), followed by fry production (20% and 10%, respectively) (Figure 2.9).

Mean eutrophication potential is higher for seabream (99 kg kg PO_4 eq ton^{-1}) than for seabass (91 kg PO_4 eq ton^{-1}) (Table 2.5), but uncertainty analysis indicated that the difference was not significant ($p = 0.32$), and identified particularly high uncertainty in seabream eutrophication potential (Figure 2.9). Eutrophication potential is dominated by fish production at the farm level (90% for both species), due to direct N and P emissions into the environment, followed by feed production (8% for both species) (Figure 2.9).

Mean global warming potential is higher for seabream (3 669 kg CO_2 eq ton^{-1}) than for seabass (3 182 kg CO_2 eq ton^{-1}), influenced mainly by feed production (2 517 and 2 463 kg CO_2 eq ton^{-1}, respectively) with contribution of 69% and 77%, respectively. Rearing practices for seabream and seabass differ mainly in fry production (618 and 269 kg CO_2 eq ton^{-1}, respectively) with a contribution of 17% and 8%, respectively (Table 2.5). Although seabream has higher mean impact than seabass, the uncertainty analysis suggested a slightly significant difference between the two ($p = 0.04$) (Figure 2.9).

Mean land occupation is slightly higher for seabream (1370 m^2 year ton^{-1}) than for seabass (1336 m^2 year ton^{-1}) (Table 2.5). This impact category is dominated by feed production (98% for both species) (Figure 2.9). However, uncertainty analysis indicated that the range of NPPuse for seabass fits within that for seabream and the difference was not significant ($p = 0.89$) (Figure 2.9).

Mean NPPuse is higher for seabream (208 174 kg C ton^{-1}) than for seabass (202 335 kg C ton^{-1}) (Table 2.5), but uncertainty analysis indicated that the range of NPPuse for seabass fits within that for seabream and the difference was not significant ($p = 0.62$) (Figure 2.9). NPPuse was due exclusively to feed production for both species (Figure 2.9).

Mean TCED is higher for seabream (57 198 MJ ton^{-1}) than for seabass (51 098 MJ ton^{-1}) (Table 2.5), but the difference is not significant when uncertainty is considered ($p = 0.17$)(Figure 2.9). TCED is dominated by feed production (71% and 80% for seabream and seabass, respectively), followed by fry production (13% and 6%, respectively) (Figure 2.9).

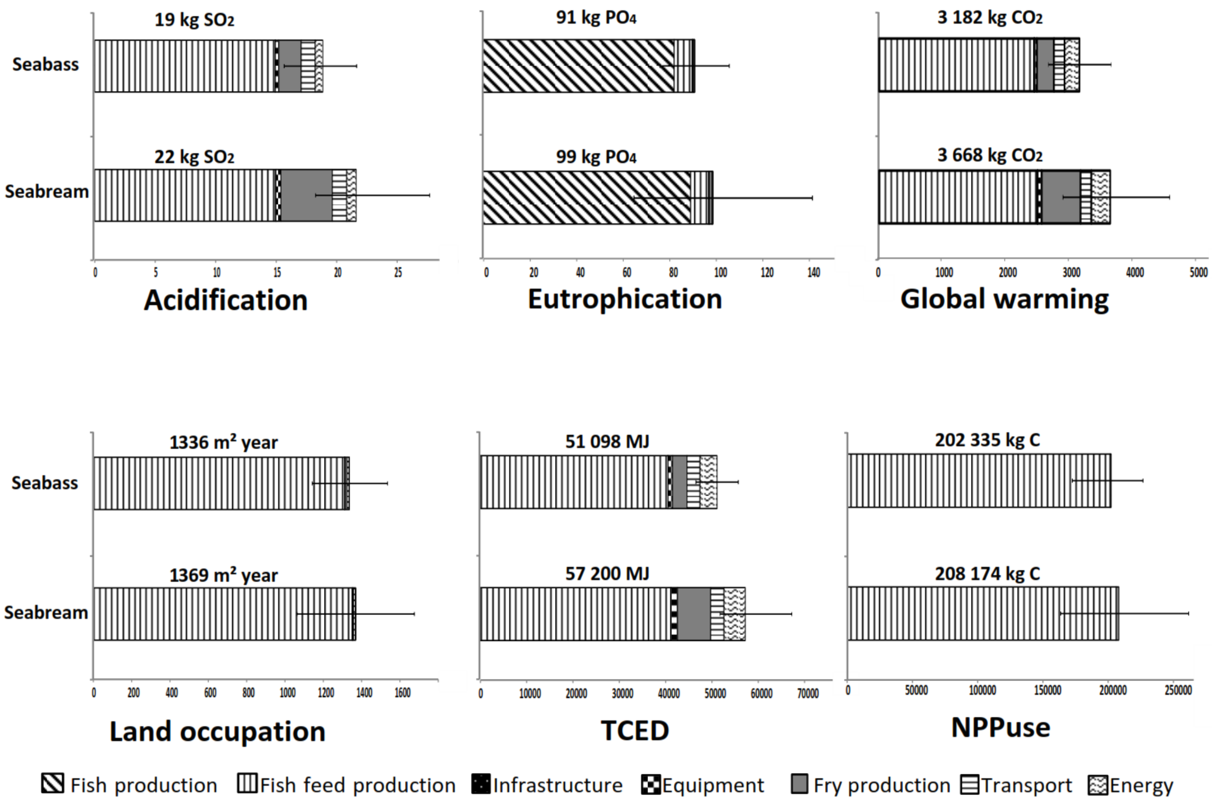


Figure 2.9 : Contribution of fish-farm components to impact categories for production of 1 ton of seabass or seabream. Bars represent mean impacts, and error bars represent 1 standard error calculated using Monte-Carlo simulations (TCED: total cumulative energy demand, NPPuse: net primary production use).

Table 2.5 : Environmental impacts per ton of seabream and seabass produced, by production component.

Impact	Fish production	Fish-feed production	Infrastructure	Equipment	Fry production	Transport	Energy	Total
Acidification (kg SO_2 eq)								
Seabream	0.00	14.96	0.01	0.42	4.26	1.19	0.78	21.61
Seabass	0.00	14.92	0.01	0.28	1.85	1.16	0.62	18.85
Eutrophication (kg PO_4 eq)								
Seabream	89.30	7.80	0.00	0.23	1.20	0.24	0.10	98.86
Seabass	82.21	7.83	0.00	0.15	0.52	0.23	0.08	91.03
Global warming (kg CO_2 eq)								
Seabream	0.00	2 517.04	1.60	64.22	617.70	170.91	297.16	3 668.65
Seabass	0.00	2 463.22	1.60	43.40	269.25	167.42	237.31	3 182.22
Land occupation (m^2 year)								
Seabream	0.00	1351.15	0.47	1.76	4.35	10.37	1.28	1369.39
Seabass	0.00	1311.38	0.47	2.55	9.99	10.58	1.60	1336.57
Total cumulative energy demand (MJ)								
Seabream	0.00	41 129.77	22.41	1411.51	7 175.27	2 852.04	4 607.86	57 198.85
Seabass	0.00	40 525.94	22.41	948.33	3 127.68	2 793.89	3 679.80	51 098.05
Net primary production use (kg C)								
Seabream	0.00	206 083.45	0.00	0.00	2 090.89	0.00	0.00	208 174.35
Seabass	0.00	201 423.65	0.00	0.00	911.41	0.00	0.00	202 335.06
Sea use (m^2 year)								
Seabream	919.15	9 179.90	0.00	0.00	71.98	0.00	0.00	10 171.03
Seabass	699.32	8971.72	0.00	0.00	31.38	0.00	0.00	9 702.41

2.3.3.2. MERAMOD predictions and sea-use impact

MERAMOD predicted that 113 100 m^2 year of seabed is damaged by operating the fish farm. Producing 2 100 t of fish (seabass and seabream) heavily impacts more than 9 600 m^2 of seabed under the sea cages, with total deposition of 100 410 kg $year^{-1}$ yielding a mean of 10.5 kg m^{-2}. An area of almost 21 000 m^2 is moderately impacted, with total deposition of 98 253 kg $year^{-1}$ yielding a mean of 4.7 kg m^{-2}. An area of 77 526 m^2 is lightly impacted, with total deposition of 67 400 kg $year^{-1}$ yielding a mean of 0.8 kg m^{-2}.

MERAMOD predictions also show that seabass rearing generates higher sea use than seabream rearing (Table 2.6). Under a single cage 22 m in diameter, total deposition equals 18 494 kg $year^{-1}$ over an area of 6 093 m^2 for seabass vs. 4 996 kg $year^{-1}$ over an area of 2 916 m^2 for seabream. The heavily impacted area is larger under a seabass cage (909 m^2 with mean deposition of 11.6 kg m^{-2} $year^{-1}$) than a seabream cage (99 m^2 with mean deposition of 8.52 kg m^{-2} $year^{-1}$). Seabream cages 29 m in diameter have more heavily impacted area (153 m^2 with mean deposition of 1277 kg $year^{-1}$) than cages 22 m in diameter (99 m^2 with mean deposition of 843 kg $year^{-1}$)(Table 2.6); however, their moderately and lightly impacted areas are similar.

Table 2.6 : Predictions of solid-matter deposition and impacted area of the MERAMOD® model for three types of cages on the fish farm (Ø: diameter).

Cage type	Solid matter deposition (kg $year^{-1}$)			Impacted area (m^2)			Mean (kg m^{-2} $year^{-1}$)		
Impact intensity	Light	Moderate	Heavy	Light	Moderate	Heavy	Light	Moderate	Heavy
Seabass (Ø 22 m)	3 550	4 404	10 541	4 257	927	909	0.83	4.75	11.60
Seabream (Ø 22 m)	1543	2 610	843	2 286	531	99	0.67	4.92	8.52
Seabream (Ø 29 m)	1859	2 824	1277	2 601	603	153	0.71	4.68	8.35

Mean sea sea use is higher for seabream (10 171 m^2 year ton^{-1}) than for seabass (9 702 m^2 year ton^{-1}), but the difference is not significant due to the high uncertainty. Sea use is dominated by feed production (90% and 92% for seabream and seabass, respectively), which requires 9 180 and 8 972 m^2 year ton^{-1} for seabream and seabass, respectively (Figure 2.10), due mainly to the area required to harvest fish (through fisheries). A large area of seabed is swept by fishing equipment to catch fish to produce fish meal and fish oil. Uncertainty analysis indicated that the range of NPPuse for seabass fits within that for seabream and the difference was not significant ($p = 0.47$) (Figure 2.10).

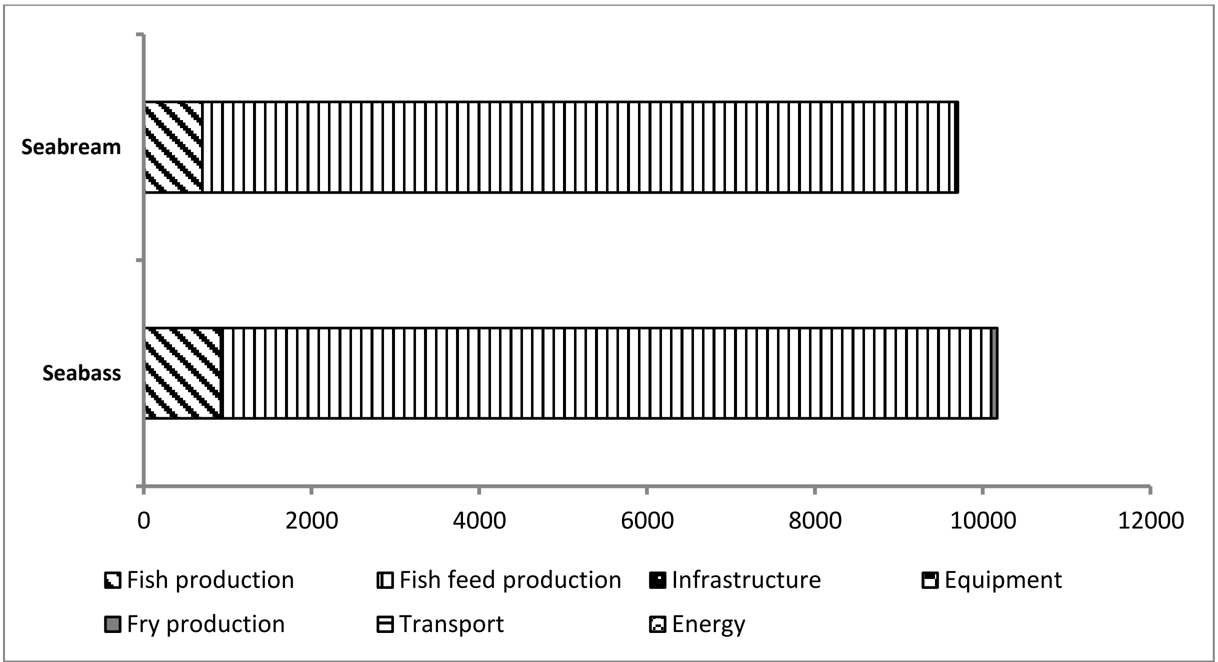


Figure 2.10 : Contribution of fish-farm components to the sea-use impact category for production of 1 ton of seabass or seabream. Bars represent mean impacts, and error bars represent 1 standard error calculated using Monte-Carlo simulations.

2.3.4. Discussion

Developing sustainable aquaculture is a priority in the current economic and social context. Therefore, aquaculture production systems must change to improve environmental performance and decrease energy consumption (d'Orbcastel et al., 2009). To achieve these objectives, a holistic perspective is needed when considering the impacts generated by production, and LCA is considered the most suitable tool for analyzing such a wide spectrum (Guinée et al., 2002). Recently, LCA has been applied to several aquaculture systems around the world (Aubin et al., 2015, 2006; Henriksson et al., 2015; Jerbi et al., 2012; Papatryphon et al., 2004). The current study estimates the environmental performance of one aquaculture farm in Tunisia and compares impacts of producing 1 ton of seabass to those of producing 1 ton of seabream.

Overall, the fish production phase appears to be the main driver of eutrophication, mainly due to feed-derived substances such as uneaten and undigested feed and waste containing both solid and dissolved N and P. Comparison of seabass and seabream production reveals higher eutrophication potential for seabream, which agrees with results of Piedecausa et al. (2010) and Sarà et al. (2011), who demonstrated that seabream farming emits more N and P than seabass farming. However, due to the high uncertainty, differences in all impacts of seabass and seabream production appear to be non-significant and can be disputed.

Comparing results from different LCA studies is challenging, mainly due to methodological differences, especially in defining the studied system and its boundaries (Henriksson et al., 2012). We compared our results to those of previous studies that used the same characterization method (CML2 baseline 2000), selected the same impact categories and were based on the same assumptions concerning the system boundaries, certain values of inputs and the level of details of some processes. This enabled comparison of relative impacts in the same categories (Chen et al., 2015).

Among seabass systems in the Mediterranean, seabass reared in sea cages in Tunisia have almost the same eutrophication potential per ton as they do in Greece (Aubin et al., 2009), and both have lower eutrophication potentials than those reared in traditional or cascade raceways in Tunisia (Jerbi et al., 2012) (Figure 2.11). Among different species, eutrophication potential per ton is highest for seabass/seabream in Tunisia and carp/tilapia in Indonesia (Mungkung et al., 2013), followed by turbot in a re-circulating system in France (Aubin et al., 2009) and trout in a flow-through system in France (d'Orbcastel et al., 2009) (Figure 2.12). This ranking is due mainly to differences in feed-derived wastes, which are directly related to feeding practices (indicated by the FCR). Moreover, the high protein content of fish feed and its fish-derived ingredients induce larger P emissions.

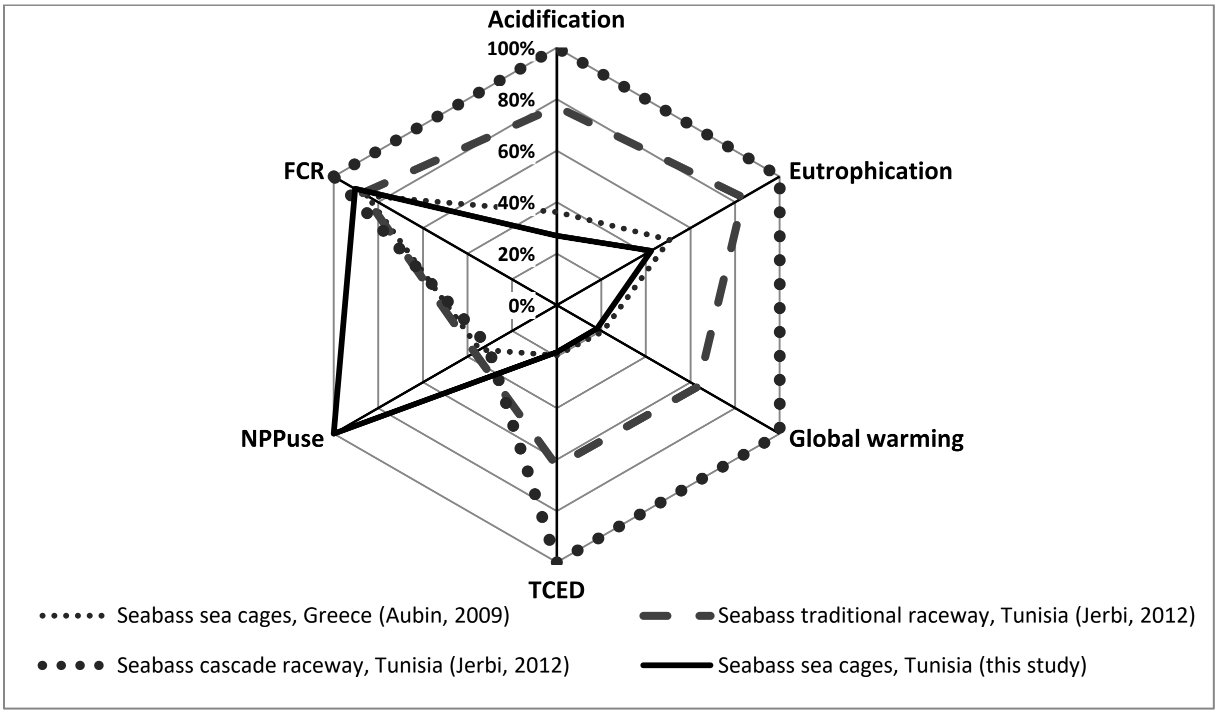


Figure 2.11 : Relative environmental impacts and feed-conversion ratios (FCR=kg of feed distributed/kg of fish produced) of four seabass aquaculture farms using different techniques (TCED: total cumulative energy demand, NPPuse: net primary production use)

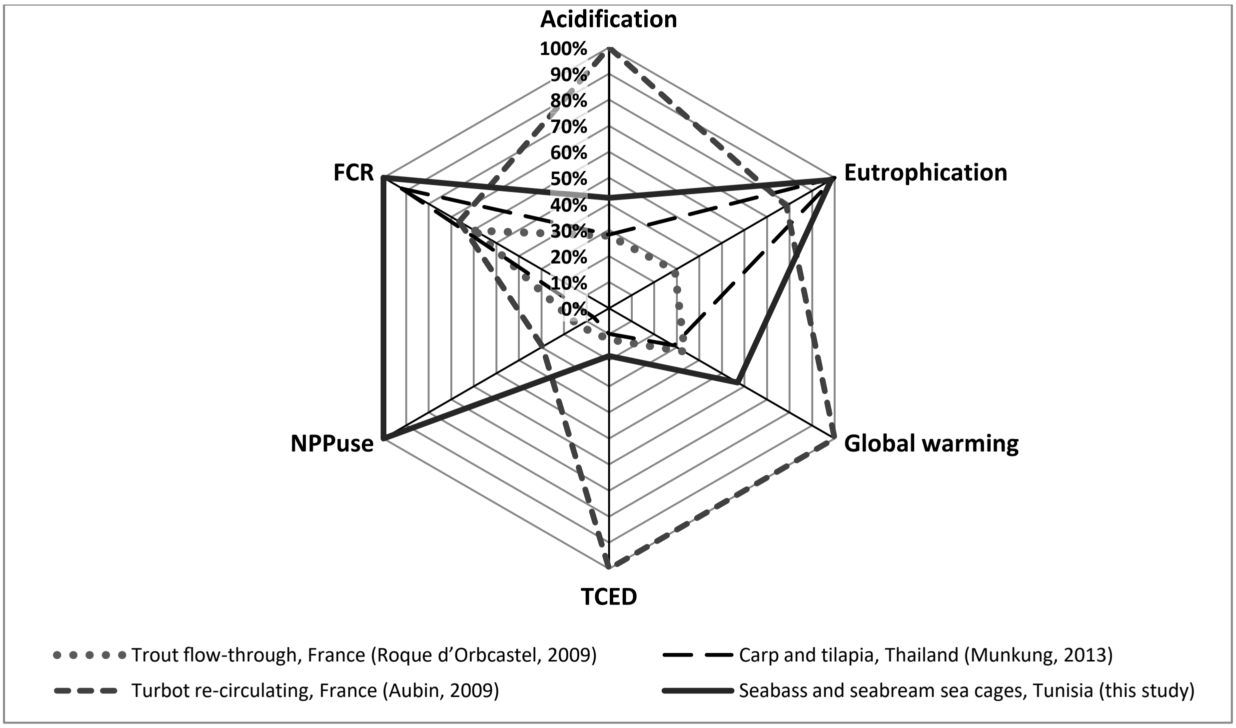


Figure 2.12 : Relative environmental impacts and feed-conversion ratios (FCR=kg of feed distributed/kg of fish produced) of four aquaculture farms raising different species. (TCED: total cumulative energy demand, NPPuse: net primary production use).

We conclude that high eutrophication impact is related to the efficiency with which fish feed is used. The higher FCR observed for seabass and seabream in the studied system is associated with the large amount of feed needed for production and the subsequent amount of related inputs (e.g. crop-based ingredients, energy). It is relatively easy to manage fish stocks and determine adequate rations for fish in tank-based rearing systems. It is more challenging, however, to manage stock with precision in sea cages on aquaculture farms, which results in low control of feed intake and high FCR. The elevated FCR reflects that the reared fish did not adequately transform the diet provided. Consequently, much fish feed is uneaten, which increases eutrophication potential and wastage of primary production.

The relevance of these results can be questioned, however, since the eutrophication impact category in LCA does not consider an ecosystem's ability to assimilate nutrients (i.e. nutrient mass per unit area that is retained permanently) (Richardson and Qian, 1999). To estimate eutrophication impact accurately, it is necessary to consider an ecosystem's ability to transform nutrients efficiently and nutrient thresholds at which ecosystem functioning and structure remain undisturbed.

Fish-feed production contributes most to the other five impact categories. This reflects the high impact of feed production, from extraction of raw materials up to manufacturing processes, which require large amounts of energy and resources. Besides its predominant environmental impact, fish feed also has a major economic impact on the aquaculture farm since all of it is imported (DGPA, 2014). Compared to other seabass rearing systems, the studied farm had higher NPPuse due to the high content of marine ingredients (fish meal and fish oil) in the diets and the amount of feed required for production (reflected by the high FCRs). For the other impact categories, per-ton impacts of seabass production on the studied farm are similar to those of a sea-cage system in Greece (Aubin et al., 2009) and are lower than those of traditional or cascade raceways in Tunisia (Jerbi et al., 2012). This is because the FCR is fundamental in determining the environmental performance of aquaculture systems. Seabream and seabass production in Tunisia had much higher NPPuse than production of other species due to the large amount of fish feed required (high FCR). The high contents of fish meal, fish oil and crop-derived ingredients in fish feed have great influence on NPPuse. This impact category has been applied in a variety of ways, and many methodological developments in NPPuse have been published recently (Cashion et al., 2016; Emanuelsson et al., 2014).

For the other impacts (acidification, global warming and TCED), turbot farming in re-circulating systems in France (Aubin et al., 2009) had the highest impacts among the systems considered. Its FCR was lower than those of seabream/seabass in our study and of carp/tilapia in Thailand (Mungkung et al., 2013). This is mainly because the re-circulating system requires a large amount of electricity, some of which is generated with fossil fuels. Although supplies of fossil fuels are limited, energy is not considered a limiting factor because technical choices in aquaculture are principally influenced by economic trends and costs. However, replacing fossil fuels with renewable energy sources can reduce acidification and global warming impacts greatly.

Uncertainty analysis shows a high range of uncertainty in all impacts due to large differences in farming practices and feeding techniques on aquaculture farms in Tunisia. The higher uncertainty in all impact categories for seabream than for seabass is directly related to management practices and techniques on the farm. Monitoring all aspects of seabream rearing remains problematic, and strategies differ among farms, which increases the uncertainty compared to seabass rearing. Uncertainty analysis indicates that certain impacts (i.e. eutrophication, land occupation, NPPuse) of seabream and seabass rearing are not significantly different.

Application of MERAMOD confirms its ability to predict impact on the seabed generated by fish farms. Impacts of nutrient release under fish farms are currently debated. Nutrient loading may negatively influence sensitive ecosystems (such as Posidonia (*Posidonia oceanica*) meadows) (Marbà et al., 2006) and benthic communities (Karakassis, 2000), but Machias et al. (2004) showed a positive impact, with an increase in sea productivity and a subsequent increase in fish communities. MERAMOD could be improved by studying the influence of solid deposition on benthic communities and biodiversity under the farm. It also would be useful to consider influence on wild fish near the farm to improve overall understanding of impacts generated by aquaculture.

Feed production contributed most to sea use because requires large amounts of fish meal and fish oil. In 2002, 46% of fish meal and 81% of fish oil produced worldwide were used for aquaculture (Tacon, 2005), and with the rapid growth of aquaculture, it is difficult to obtain alternate sources of protein and lipids. Research is underway to identify plant-based ingredients to replace fish meal and fish oil in aquaculture feed (Dias et al., 2009). The use of wild-fish protein in fish feed is debatable, especially when aquaculture is compared to fishing (Ellingsen and Aanondsen, 2006). The trend toward plant-based ingredients will not only decrease dependence on wild-fish meal and oil but also potentially improve the FCR and decrease environmental impacts while ensuring better economic profitability. However, replacement of fish meal and oil still faces several biological constraints that are difficult to overcome. Aquaculture feed used by farms in Tunisia contain high amounts of fish meal and fish oil (66%). However, this formulation is considered as "outdated", because the majority of fish feed used in seabass and seabream rearing contain between 20% and 45% of marine-derived ingredients (Tacon and Metian, 2008).

The main objectives for the studied farm are to decrease nutrient loading and feed wastage; both require improving feeding efficiency and feed composition to decrease the FCR. Doing so will improve environmental performance and maintain economic profitability (Papatryphon et al., 2004). Appropriate stock-management practices (controlling the size and number of fish) are crucial, as are efficient feeding practices, which are achieved by controlling technical aspects (e.g. timing and method of distributing feed pellets) (Cripps and Bergheim, 2000). Fish feed is a major economic issue for all Tunisian aquaculture; thus, building a feed-production facility would help reduce environmental impacts and increase the sustainability of aquaculture. Fish farming in Tunisia must pursue two main objectives: decrease energy use (due to changes in energy costs) and decrease nutrient emissions (which can be supported by environmental regulations). One major unknown is the future availability of fish meal and fish oil for feed production. Declines in fisheries stocks may decrease fish meal and fish oil production and consequently feed production, which is a necessity for Tunisian aquaculture. In the current context, an increase in aquaculture poses a serious threat to the environment. Therefore, the government and the private sector should act together to ensure the long-term sustainability of fish farming. The public sector should encourage research and development of environmentally conscious aquaculture systems and enforce regulations that protect the marine environment. The private sector should also recognize that current practices need to improve. Applying a few of these improvement measures could help decrease external costs of aquaculture, while current trends could promote a more sustainable sector.

In order to provide more accurate estimates of aquaculture's environmental impacts it is important to create new impact categories custom-built for aquaculture. These impact categories should be adapted to the fish farming sector to capture its environmental, economic and social interactions. This study would also be improved if more farm data were available. It would be useful to extend boundaries of the studied system to include downstream processes related to aquaculture, such as packaging, distribution and use of the fish produced. As a "cradle-to-grave" study, estimates could be generalized to the entire life cycle of production. In addition, MERAMOD predictions can be improved by considering resuspension of waste and determining several layers of current circulation under the cages.

2.3.5. Conclusion

This study provided a comprehensive evaluation of environmental performances associated with production of seabass and seabream on a sea-cage aquaculture farm in Tunisia. The estimated environmental impacts were expressed per ton of live fish. Based on this analysis, we conclude that seabass rearing has lower impacts than seabream rearing for all the impact categories studied; however, differences do not appear significant when considering uncertainty in input data for all the impact categories except the global warming. Overall, this study reveals that feeding management is the main contributor to most of the studied impacts, which is related to the large amounts of N and P released into the environment. Measures that optimize production and use of fish feed will positively influence environmental performance of the farm. Fish reared on the farm require large amounts of protein and lipids, which are provided mainly by fish meal and fish oil from wild-fish stocks. Therefore, it is essential to optimize diet formulation and follow better feeding strategies to lower the FCR and consequently improve the environmental performance of the aquaculture farm.

It is beyond the scope of the current study to identify impacts that should be given highest priority; however, the study does indicate several hotspots for improvement. The results gathered from the LCA provide information to support decision-making and investigation of ways to improve production-system strategies to improve the environmental performance and sustainability of aquaculture. The multi-criteria approach of the LCA covers several scales and provides general estimates of environmental impacts associated with producing 1 ton of fish. However, including impacts related to biodiversity and the biology of the reared species could supplement and improve the analysis. It is also important to create new impact categories adapted to the fish farming sector to capture its environmental, economic and social interactions. This study would be improved, if more farm data were available, by extending the boundaries of the studied system to include downstream processes related to aquaculture.

2.4. Conclusion et perspectives du chapitre

Dans le contexte socio-économique actuel, le développement d'une aquaculture durable représente une priorité en Tunisie. L'objectif principal de ce chapitre était d'étudier les impacts environnementaux reliés à l'aquaculture. Dans un premier temps, l'ACV a été appliquée à toutes les fermes aquacoles spécialisées dans l'élevage du bar et de la daurade dans des cages en mer. Ensuite, la même méthodologie d'ACV a été appliquée à une seule ferme aquacole en ajoutant une nouvelle catégorie d'impact qui reflète l'impact sur les surfaces et les fonds marins.

Les résultats obtenus dans ce chapitre montrent les relations et les chaînes de causalité entre les pratiques d'élevage aquacoles en Tunisie et les modifications environnementales. Ces résultats permettent aussi de formuler des recommandations pour l'amélioration des performances environnementales de l'aquaculture par ACV.

Ce chapitre a montré que l'intensité des impacts environnementaux n'est pas liée à la production des fermes aquacoles mais plutôt aux pratiques aquacoles et à la production d'aliments de poisson, qui sont les contributeurs majeurs aux impacts. Ceci est expliqué par l'utilisation de farine et d'huile de poisson dans la fabrication de l'aliment, ce qui génère des émissions importantes d'azote et de phosphore dans l'environnement. L'aliment aquacole fait partie des enjeux économiques majeurs en Tunisie étant donné que la totalité des aliments utilisés dans les fermes d'aquaculture est importée. Le ratio de conversion d'aliment, la profondeur sous les cages aquacoles et la taille des cages utilisées sont les caractéristiques techniques qui influencent le plus l'intensité des impacts environnementaux. La comparaison entre les deux espèces élevées en Tunisie a montré que les impacts environnementaux engendrés par la production du bar sont inférieurs à ceux reliés à la production de la daurade, mais la différence entre les deux bilans environnementaux n'est pas significative.

Ces résultats révèlent l'importance de la mise en place des mesures d'amélioration des pratiques aquacoles pour assurer la durabilité du secteur aquacole. Optimiser la formulation de l'aliment aquacole aura une influence positive sur le bilan environnemental des fermes d'aquaculture, puisque les protéines et les lipides requis par les poissons proviennent principalement de la farine et de l'huile de poisson. Il est également important d'améliorer les stratégies d'alimentation de poissons ainsi que les pratiques d'élevage (distribution d'aliments, rationnement efficace, bonne gestion des stocks de poissons, etc). Il serait judicieux que les autorités encouragent les fermes aquacoles à se développer dans un contexte de durabilité en respectant l'environnement. Les autorités devraient favoriser les fermes aquacoles ayant des cages plus larges et une profondeur d'eau importante sous les cages et les encourager à diminuer leur ratio de conversion d'aliments.

L'analyse environnementale peut être améliorée en incluant des catégories d'impacts plus spécifiques à l'activité aquacole. Ces catégories doivent prendre en compte les caractéristiques environnementales, économiques et sociales de l'aquaculture, mais cela nécessite beaucoup de données spécifiques aux fermes aquacoles. Un autre aspect qui peut être amélioré est l'intégration des étapes post-production (emballage, distribution, commercialisation, utilisation, recyclage, etc) ce qui permettra de passer d'une étude "du berceau à la porte de la ferme aquacole" à une étude "du berceau à la tombe". La précision des prédictions du modèle MERAMOD peut aussi être renforcée en prenant en considération la remise en suspension des matières organiques déposées (fèces et aliments non consommés ou non digérés) et en ajoutant plusieurs niveaux de circulation des courants d'eau sous les cages aquacoles.

En conclusion, l'ACV propose une vision holistique sur les impacts environnementaux des systèmes de production piscicole. C'est une méthode qui va au-delà du simple bilan environnemental puisqu'elle permet d'indiquer les processus à améliorer pour avoir une meilleure performance globale.

Chapitre 3

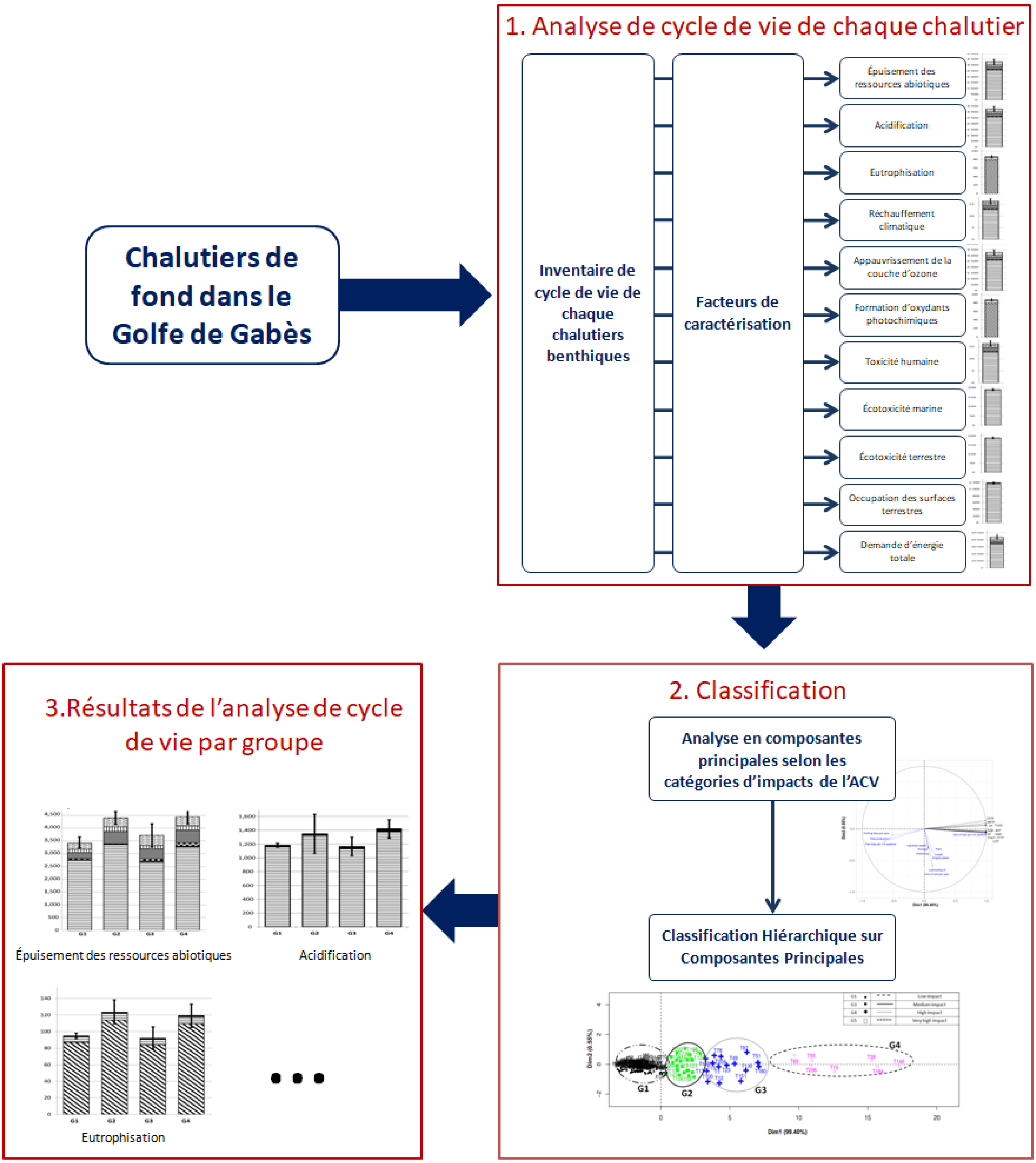
Application de l'Analyse du Cycle de Vie au secteur de la pêche au chalut de fond en Tunisie (Golfe de Gabès)

3.1. Introduction du chapitre

L'objectif de ce chapitre est d'évaluer les impacts environnementaux de l'activité de la pêche au chalut de fond dans le Golfe de Gabès. Le Golfe de Gabès est un haut lieu de pêche en Tunisie et il assure plus de 40% de la production halieutique tunisienne. Le chalutage de fond est l'activité prédominante dans le golfe. La plupart des études environnementales se sont focalisées sur les impacts engendrés par la pêche sur les stocks ciblés, sur les espèces et sur les réseaux trophiques (Bănaru et al., 2013; Cook et al., 2013; Espinoza-Tenorio et al., 2015; Gascuel et al., 2016; Shannon et al., 2014).

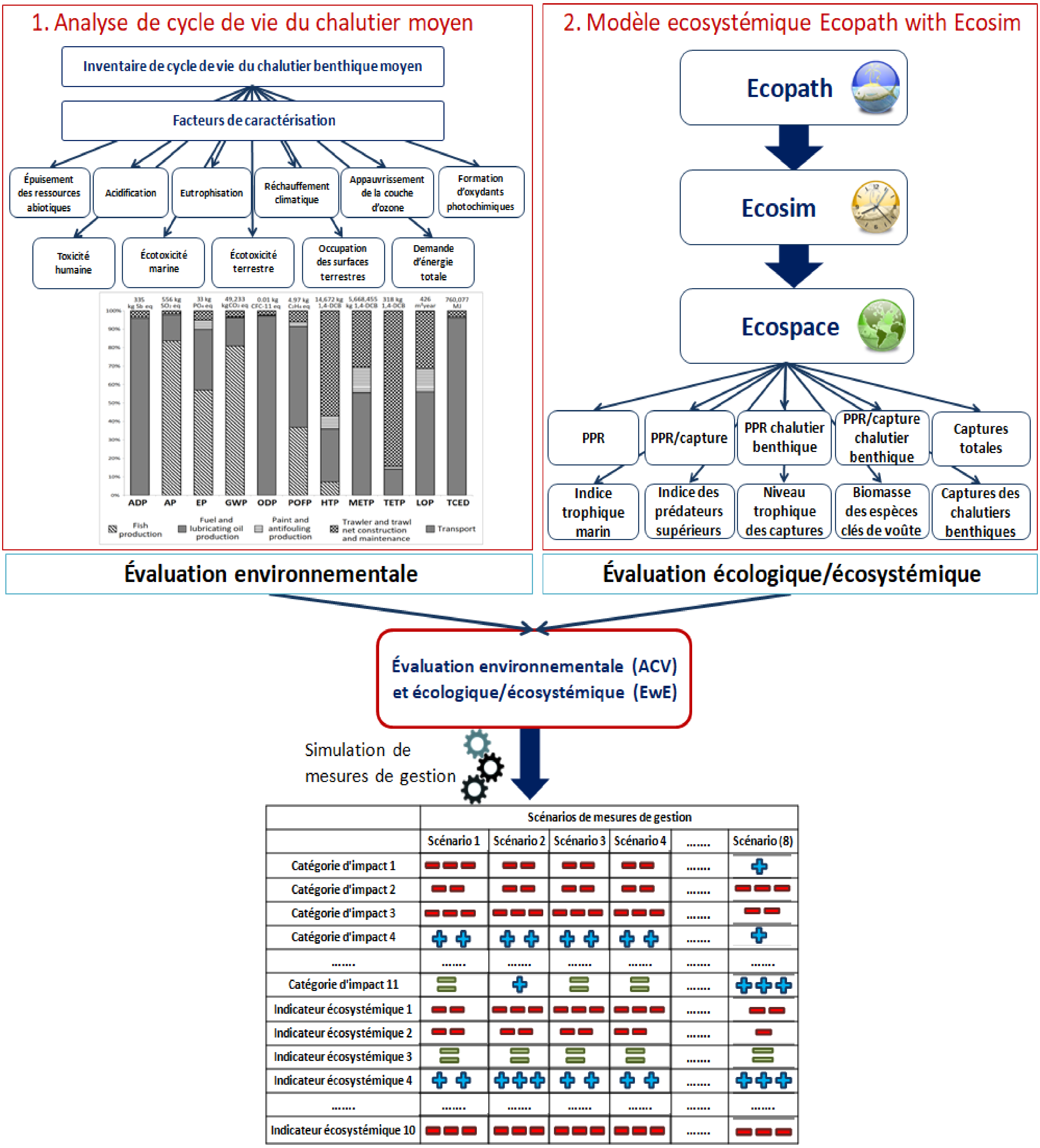
Ce chapitre s'appuie sur deux articles. Dans le premier article, publié dans le journal "Science of the Total Environment" (manuscrit C, Abdou et al. (2018), section 3.2 du présent chapitre), l'ACV a été mise en œuvre pour évaluer les conséquences environnementales liées à la production d'une tonne de produits de la mer par les chalutiers de fond à coque en bois dans le Golfe de Gabès. L'analyse a pris en considération tous les processus intervenant dans la production du poisson, depuis la construction des chalutiers et des chaluts jusqu'à leur utilisation pour la pêche, l'importation de matières premières pour la construction du bateau, le transport et la consommation en énergie fossile. Faute de données fiables, l'ACV dans cette étude ne couvre pas la fin de vie du produit ni les étapes post-débarquement (emballage, stockage, distribution, etc). Les catégories d'impacts étudiées sont l'épuisement des ressources abiotiques, l'acidification, l'eutrophisation, le réchauffement climatique, l'appauvrissement de la couche d'ozone, la formation d'oxydants photochimiques, la toxicité humaine, l'écotoxicité marine, l'écotoxicité terrestre, l'occupation des surfaces terrestre et la demande d'énergie cumulée. Dans un premier temps, l'ACV a été appliquée à chaque chalutier individuellement. Ensuite, les chalutiers ont été classés selon l'intensité des différents impacts en utilisant une analyse en composantes principales suivie d'une classification hiérarchique. Les résultats sont agrégés par groupes de chalutiers.

Résumé graphique de la méthodologie utilisée dans le manuscrit C (Abdou et al., 2018)



Le deuxième article est soumis dans le journal "Science of the Total Environment" (manuscrit D, Abdou et al. in prep, section 3.3 du présent chapitre). Le but de cette étude est d'appuyer les résultats des catégories d'impact de l'ACV par des indicateurs de qualité de l'écosystème, de manière à prendre en compte la composante écologique dans l'analyse environnementale. Le modèle Ecopath with Ecocim (EwE) été utilisé pour le calcul des indicateurs écosystémiques. Les indicateurs inclus sont : production primaire requise (PPR), PPR/capture, PPR relatif aux chalutiers de fond, PPR/capture relatif aux chalutiers de fond, captures totales, captures des chalutiers de fond, indice trophique marin, indice des prédateurs supérieurs, niveau trophique des captures, biomasse des espèces clés de voûte. Ensuite, le module spatialisé d'EwE, Ecospace, a été développé pour évaluer les conséquences environnementales et écosystémiques de différents scenarios de gestion dans le Golfe de Gabès. Les scénarios consistent à mettre en place des mesures de gestion relatives à l'implémentation des aires marines protégées, la prolongation de la période du repos biologique (période de fermeture de la pêche) et la diminution du nombre de chalutiers.

Résumé graphique de la méthodologie utilisée dans le manuscrit D



3.2. Manuscrit C “Environmental life cycle assessment of seafood production: a case study of trawler catches in Tunisia”

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Abstract

The Gulf of Gabes is one of the most productive fishery areas in the southern Mediterranean Sea. It is archetypal of an ecosystem in which the effects of fisheries are most pronounced. Demersal trawling is the main fishing activity in the Gulf of Gabes. Life Cycle Assessment (LCA) was applied to assess the environmental performance landing 1 t of seafood with wooden demersal trawlers in the Gulf of Gabes. Impact categories included in the study were abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone depletion potential (ODP), photochemical oxidant formation potential (POFP), human toxicity potential (HTP), marine eco-toxicity potential (METP), terrestrial eco-toxicity potential (TETP), land occupation potential (LOP), and total cumulative energy demand (TCED). Demersal trawlers were classified based on their impact intensity. Results showed that 70% of the vessels had relatively low impacts. Impact intensity was proportional to the amount of fuel consumed to land 1 t of seafood. Ships that fished less had the highest impacts per ton, due to lower fishing effort and catch per unit effort. This is likely to typify vessels that target highly valuable species such as shrimp. Onboard vessel activities contributed most to different environmental impacts (AP, EP, GWP and POFP), related to the high energy use of this fishery. Several impacts (ADP, ODP, METP, LOP and TCED) were associated mainly with fuel and lubricating oil production. Therefore, improvements must focus on minimizing fuel consumption. LCA is a valuable tool for assessing how to increase environmental sustainability of demersal trawling and it can help stakeholders identify the main operational issues that require improvement.

Keywords: Life Cycle Assessment, Demersal trawling, Environmental impact, Gulf of Gabes.

3.2.1. Introduction

Seafood represents a very important source of protein for the world's population. In 2014, seafood accounted for about 17% of the global population’s intake of animal protein and 6.7% of all protein consumed (FAO, 2016). Due to the increase in world population and the increasing demand for seafood over the last decades, fishing activities have expanded substantially (Halpern et al., 2008). This expansion is related to technological developments in fishing technologies, increased fishing effort, increased number of fishing units and fishing grounds (Pauly et al., 2002; Swartz et al., 2010). Global production from marine fisheries increased to 86 million tons in 1996 and is now stagnating, and even slightly decreasing, due to the overexploitation of many fish stocks (FAO, 2016). Based on the Food and Agriculture Organization, half of world's fisheries are fully exploited and only 25% are sustainably exploited (FAO, 2016).

The Mediterranean Sea is the widest and deepest semi-enclosed sea in the world (Lotze et al., 2011). It is considered a biodiversity hotspot despite its oligotrophic conditions (Coll et al., 2010). Due to a long history of exploitation, the Mediterranean Sea has experienced several perturbations related to human impacts (Libralato et al., 2008; Tsagarakis et al., 2010). Fishing is the main threat to the Mediterranean ecosystem, in addition to climate change, eutrophication, habitat loss, pollution and introduction of alien species (Coll et al., 2010; Ben Rais Lasram et al., 2015a). The Gulf of Gabes, located on the southeastern coast of Tunisia, has a shallow slope, soft bottom and high fish diversity. The gulf is the main fishing ground in the country (more than 40% of national seafood production) and is one of the most productive areas in the Mediterranean Sea in terms of catches (Halouani et al., 2015b; Papaconstantinou and Farrugio, 2000).

Fishing is the only food production activity that relies mainly on extracting organisms from wild ecosystems (Christensen et al., 2003), which risks degrading marine ecosystems (Kaiser and de Groot, 2000). Environmental impacts of seafood production have been studied widely in recent years because of increased worries concerning world fisheries state (World Bank, 2017; Worm et al., 2009). Most studies focused on direct impacts of fisheries on targeted species (Costello et al., 2016; Myers and Worm, 2003; Pauly et al., 2002) by-catch and discarded organisms (Glass, 2000); changes in benthic communities (Guyonnet et al., 2008); seafloor damage due to trawling (Hall–Spencer et al., 2002; Kaiser et al., 2006) and changes in trophic dynamics, structure and functioning of the ecosystem (Jackson et al., 2001; Pauly et al., 2002; Tremblay-Boyer et al., 2011). Most environmental studies focus on these general concerns and overlook important aspects related to the performance of fishing. Few studies include impacts related to energy and material use in the construction and maintenance of fishing vessels (Hayman et al., 2000), supply of gear (Ziegler et al., 2003), gear loss at sea (Derraik, 2002), fuel consumption (Thrane, 2004; Tyedmers et al., 2005), ice, paint and antifouling paint (Hospido and Tyedmers, 2005) and marketing and processing catches (Andersen, 2002).

The long-term sustainability of fishing is a major concern from environmental and ecological viewpoints. Social groups (e.g. authorities, stakeholders, consumers, skippers) require a complete evaluation of environmental impacts of seafood products, which is reflected in recent developments and policies, such as increasing consumer awareness (FAO, 2016; Luten, 2006). To better understand environmental impacts and ensure the sustainability of fishing, it is necessary to develop an integrative science-based approach to impact assessment. In this context, Life Cycle Assessment (LCA) has emerged as a robust method to estimate potential environmental impacts associated with seafood production throughout the supply chain (Pelletier et al., 2007).

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). It is an ISO-14000 standardized method (ISO, 2006a, 2006b). LCA of fisheries and seafood products began in the 2000s (Avadí and Fréon, 2014) and has been applied to a wide range of seafood products (Tyedmers, 2000; Ziegler et al., 2003, 2011; Hospido and Tyedmers, 2005; Iribarren et al., 2010; Vázquez-Rowe et al., 2010, 2012b; Ramos et al., 2011; Fréon et al., 2014; Avadí et al., 2015; Abdou et al., 2017a, 2017b).

Demersal trawling is the dominant fishing practice worldwide for catching demersal and benthic species. It is also considered to have the most destructive fishing gear because it damages bottom habitats and perturbs benthic communities, in addition to its non-selectivity (Kumar and Deepthi, 2006). Using the wooden demersal trawlers operating in the Gulf of Gabes as a case study, the main objective of this study was to assess environmental impacts of trawler subfleets to analyze the environmental performance of extracting seafood using this fishing method and to identify hotspots that need to be improved to increase its environmental sustainability. To the best of our knowledge, this study represents the first fishery LCA study in the southern Mediterranean.

3.2.2. Materials and methods

3.2.2.1. Study area

Located in the south-central Mediterranean Sea, the Gulf of Gabes covers approximately 35,900 km2 (Figure 3.1). The gulf is highly sensitive to atmospheric changes (Natale et al., 2006) due to the shallowness of its basin: it remains only 50 m deep 110 km offshore. Its tidal amplitude can reach 1.8 m high (Sammari et al., 2006). Its water temperature ranges from 13-29°C (Ben Ismail et al., 2010). The Gulf of Gabes shelters one of the world’s largest Posidonia oceanica seagrass beds (Batisse and Jeudy de Grissac, 1998), which serves as a nursery, feeding and breeding habitat for many marine species (Hattour, 1991). The ecosystem offers suitable shelter for approximatively 247 fish species (Bradai et al., 2004). Human activities are a great threat to the Gulf (Lamon et al., 2014), along with changes in its biodiversity and functioning (Ben Rais Lasram et al., 2015b). Despite its oligotrophic conditions, the Gulf of Gabes is one of the most productive ecosystems in the Mediterranean (Papaconstantinou and Farrugio, 2000; Halouani et al., 2015b). Most of its seafloor has a soft bottom (Brahim et al., 2003), resulting in the prevalence of demersal trawling. Due to intense fishing activity since the early 1980s, several stocks have been identified as highly or over exploited (Fiorentino et al., 2008), and total production has substantially decreased since the 1990s. Seafood production from demersal trawlers in the Gulf of Gabes was 10,208 t in 2015, supplying approximately 41 million € (DGPA, 2015). Demersal trawling is the main fishing method in the Gulf of Gabes (Hattab et al., 2013; Mosbah et al., 2013) , with 226 fishing units in 2015, of which most (184) were wooden vessels (DGPA, 2015) that target shrimp and demersal finfish (Sparidae (Diplodus annularis, Sparus aurata), mullets (Mullus barbatus, M. surmuletus), rays (e.g. Raja clavata) and sharks (e.g. Mustelus mustelus)). The number of trawlers increased annually from 1980-1991 to 285, followed by a decrease to 229 in 1997. From 1997-2010, the number of trawlers fluctuated around approximately 250 (DGPA, 2015).

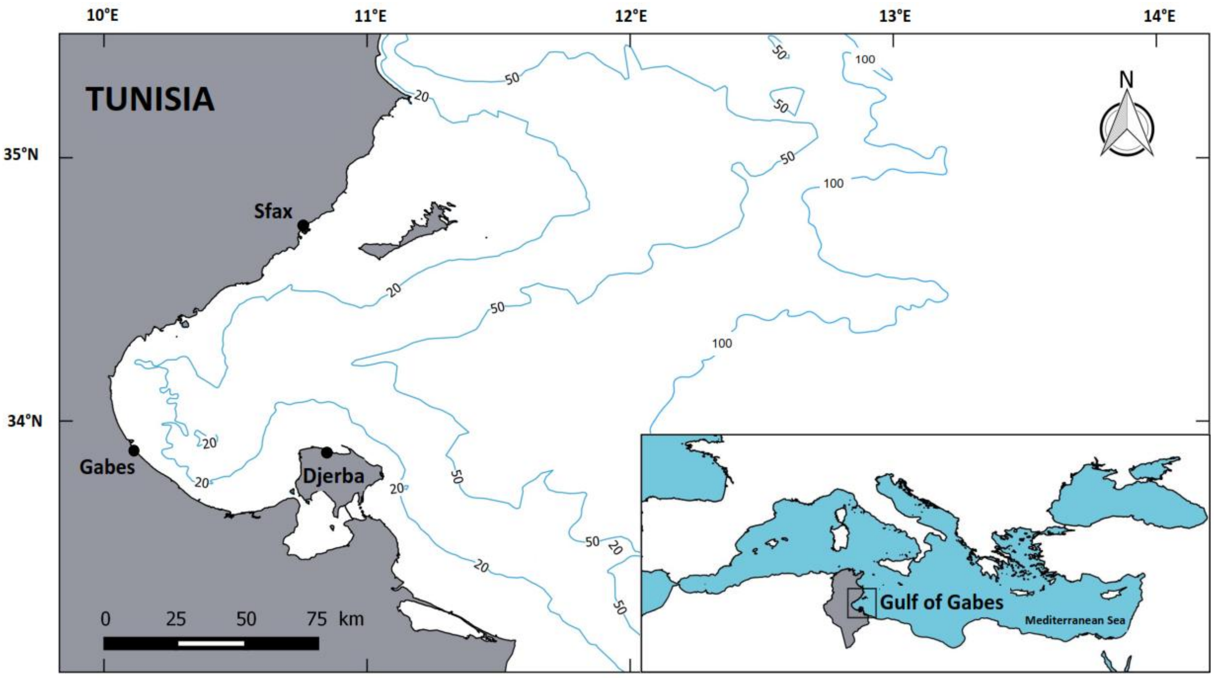

Figure 3.1 : Geographic location of the study area in Tunisia, the Gulf of Gabes ecosystem.

3.2.2.2. LCA goal and scope

An attributional LCA was performed according to the ILCD (European Commission, 2010); it consists of four phases: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation (ISO (The International Organization for Standardization), 2006a). The first step, goal and scope definition, delimits the studied system boundaries and defines the functional unit (FU), which provides a reference for inputs and outputs (ISO, 2006b).

The goal of the LCA was to describe environmental impacts associated with wooden demersal trawling in the Gulf of Gabes. The FU chosen for this study was one t of landed seafood by demersal trawlers in the Gulf of Gabes. The main objective of the study was to analyze the contribution of each production stage to environmental impacts and to understand the major drivers of environmental impacts associated with demersal trawling. Thus, we did not allocate impacts between co-products (i.e. different species landed).

The fishing fleet selected provides 22% of total Tunisian seafood production in the Gulf of Gabes and 98.5% of the annual landings in the port of Sfax (the largest port in the Gulf of Gabes) (DGPA, 2015). 184 wooden vessels in the Gulf of Gabes were selected for this study. The system includes operational stages related to seafood extraction by wooden demersal trawlers in the Gulf of Gabes (Figure 3.2):

- Fish production: reflects essentially onboard activities, emissions related mainly to the use and combustion of fuel and lubricating oil, and release of paint and antifouling substances into the water, air and soil
- Trawler and trawl net construction and maintenance: materials, energy and emissions related to the construction and maintenance of the trawler (e.g. wood, steel, paint, antifouling paint), the trawling gear, the engine and the electricity network.
- Paint and antifouling paint production: materials and energy required to produce the paint and antifouling paint necessary to construct and maintain the trawling vessels
- Fuel and lubricating oil production: materials, energy and emissions related to production of fuel and lubricating oil

- Transport: materials and energy related to marine and inland transport of imported materials

The vessels' end-of-life stages (e.g. material recycling, disposal of certain materials) and certain post-landing stages (e.g. sorting and packaging, sale, use, processing) were excluded due to lack of reliable data (Figure 3.2). The LCA is considered "cradle-to-gate" (Guinée et al., 2002) because the final product was 1 t of seafood landed at the port gate. The inventory was compiled and environmental impacts were predicted for each demersal trawler separately. This fishery was included in the previously published ecosystem models Ecospace for the Gulf of Gabes (Abdou et al., 2016).

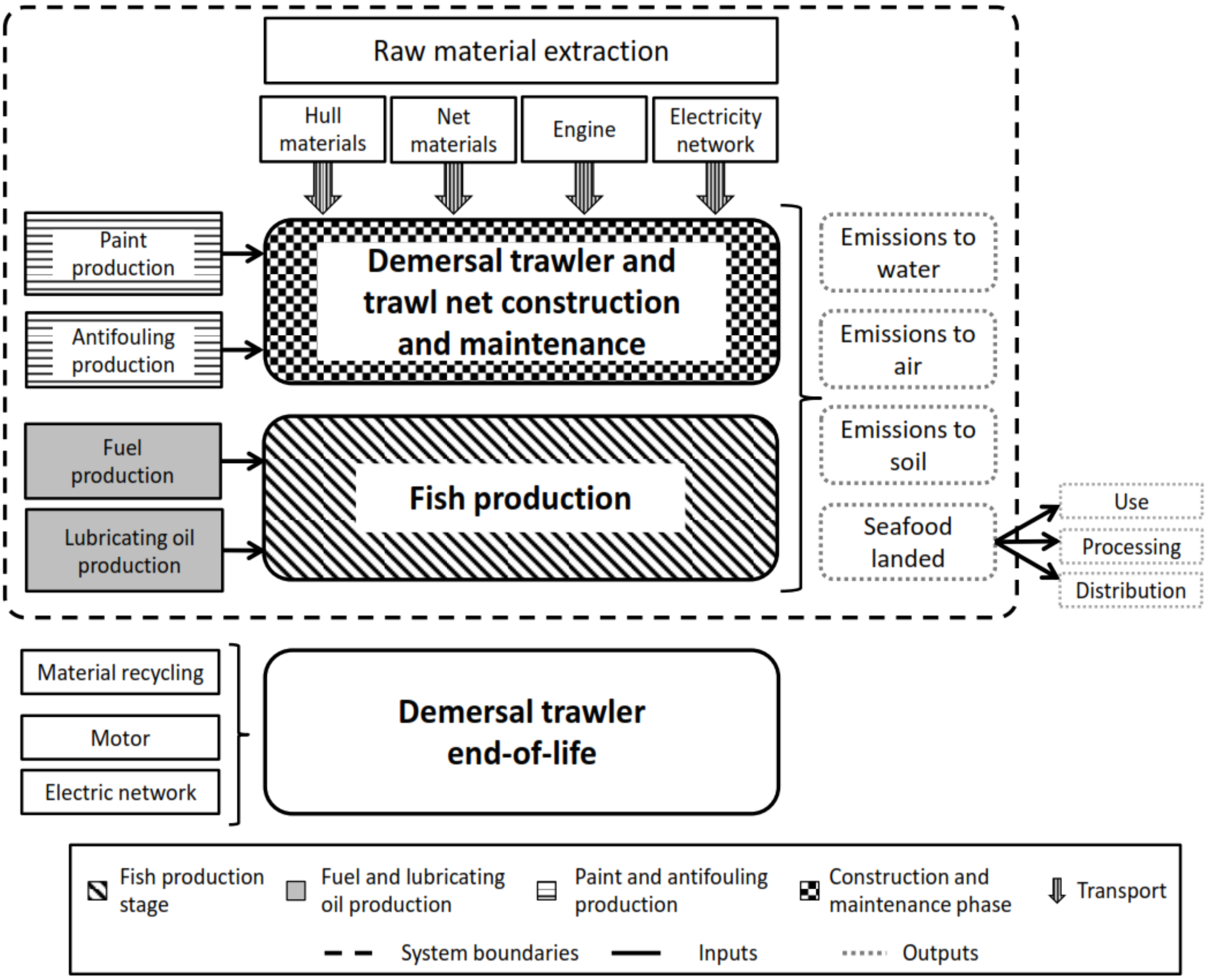

Figure 3.2 : Diagram of system boundaries and stages of demersal trawling in the Gulf of Gabes, Tunisia.

3.2.2.3. Life Cycle Inventory (LCI)

The LCI phase consists of compiling the inventory and combining the primary data (collected for the study) and secondary data (available in international databases). Data were collected for the year 2015. Landings and main vessel characteristics (e.g. length, tonnage, engine, engine power, lightship weight) were obtained from official Tunisian Direction Générale de la Pêche et de l'Aquaculture (DGPA) records for each vessel. Additional data were obtained from surveys with demersal trawler skippers and fishermen in the port of Sfax. Questionnaires included operational aspects (e.g. fuel consumption, number of fishing trips, number of days at sea). Surveys were also conducted in the Sfax shipyard to collect data on the building of trawling vessels and trawl nets (e.g. material used for construction, paint and antifouling paint quantities, dimensions of vessels, life span). The collected data were used to supplement and validate DGPA statistics. Paint and antifouling paint composition was obtained from material safety data sheets and validated by managers of the principal paint producing company in Tunisia. Emissions from paint and antifouling paint were included in the inventory (i.e. xylene, copper oxide compounds and zinc compounds) following the assumption that two-thirds of the paint and antifouling paint used is released into the water (Hospido and Tyedmers, 2005). To represent vessel maintenance and repair, we added 25% of the total amount of wood used for vessel construction (Tyedmers, 2000). The mean lifespan of wooden demersal trawlers in the Gulf of Gabes is estimated at 40 years.

Although fuel consumption is the main cost of demersal trawling, skippers rarely keep records of fuel consumption. Therefore, fuel quantities were estimated based on data from multiple confidential and anonymous sources (scientific and companies' managers). The sources provided data on the amount of fuel consumed per day and/or per fishing trip, as well as fuel consumption as a function of engine power and brand. By knowing each vessel's number of fishing trips in 2015, trip durations, and engine power and brand, we estimated its total annual fuel consumption. Then, emissions associated with fuel combustion were calculated based on the EMEP/EEA air pollutant emission inventory guidebook (EMEP/EEA, 2016). Required background data were extracted from the ecoinvent 3.0 database (Weidema et al., 2013). We excluded solid waste and waste related to daily life onboard because they are not directly connected to production (Ziegler et al., 2003) and tend to contribute little to environmental impacts (Hospido and Tyedmers, 2005). The inventory for seafood production by demersal trawling in the Gulf of Gabes is presented in Appendix 3.; however, detailed inventory and quantities could not be provided due to confidentiality.

3.2.2.4. Life cycle impact assessment

Inventory data were aggregated into impact categories and calculated per t of seafood landed. CML baseline 2000 method was selected as the computational framework to perform the life cycle impact assessment. SimaPro® 8.0 software was used to execute the computational implementation of the inventories and calculate the environmental impacts (Goedkoop et al., 2008).

Eleven of the most commonly used impact categories were included in the assessment:

- Abiotic Depletion Potential (ADP): represents the decrease in non-renewable and renewable abiotic resources that are available for human use. It is calculated following the equation $\frac{\text{extraction}}{(\text{ultimate reserve})^2}$ and then conventionally compared to the ADP of antimony (Sb); it is expressed in kg Sb equivalent (eq).
- Acidification Potential (AP): represents negative acidic effects on water and soil that are generated by production. It was estimated using the mean characterization factor (CF) for European acidification potential (Huijbregts, 1999) and is expressed in kg SO_2 eq.
- Eutrophication Potential (EP): represents the negative effects of discharging nitrogen and phosphorus in the environment. It was estimated using CFs developed by Impact World+ (Helmes, 2012) and is expressed in kg PO_4 eq.
- Global Warming Potential (GWP): represents effects of greenhouse gas emissions that increase the absorption of heat-radiation, thus increasing temperature in the lower atmosphere and resulting in climate change, which is considered a major threat to global ecosystems (Rockström et al., 2009). It was calculated based on the GWP over a 100-year time horizon (GWP100) according to the UN Intergovernmental Panel on Climate Change (IPCC, 2014); it is expressed in kg CO_2 eq.
- Ozone Depletion Potential (ODP): represents potential damage to the stratospheric ozone layer caused by chlorinated and brominated chemicals, which increase the amount of harmful ultraviolet light hitting the earth’s surface. ODP values are relative

to the ODP of chlorofluorocarbons-11 (CFC-11); ODP is expressed in kg CFC-11 (Hauschild and Wenzel, 1998).

- Photochemical Oxidant Formation Potential (POFP): represents negative impacts of chemical substances formed in the troposphere that are mainly caused by sunlight reacting to certain fossil fuel emissions (reactive substances). Photochemical oxidants are particularly dangerous to human health and ecosystems (Baumann and Tillman, 2004); POFP is expressed in kg ethylene (C_2H_4) eq.
- Human Toxicity Potential (HTP): represents potential harm caused by chemicals released into water, air or soil. It includes the inherent toxicity of a pollutant and its dose. For each toxic substance, HTP is expressed in kg 1,4-dichlorobenzene (1,4-DCB) eq.
- Marine Eco-Toxicity Potential (METP): represents negative effects of toxic substances on marine ecosystems. METP is calculated from the USES-LCA method, which defines the fate, exposure and effects of toxic emissions related to each product used as input in production; it is expressed in kg 1,4-DCB eq.
- Terrestrial Eco-Toxicity Potential (TETP): represents negative impacts of toxic substances on terrestrial ecosystems. It is calculated in the same way as METP and is expressed in kg 1,4-DCB eq.
- Land Occupation Potential (LOP): represents the land area required, expressed in m^2year.
- Total Cumulative Energy Demand (TCED): represents the amount of energy (e.g. fossil fuels, electricity) required. It was estimated based on lower heating values in SimaPro (Pré Consultants, 1997) and is expressed in megajoules (MJ).

Each impact was calculated for each demersal trawler separately. Principal Component Analysis (PCA) and Hierarchical Clustering on Principal Components (HCPC) were then performed to develop a typology of demersal trawlers based on their impact intensity. PCA is considered an effective approach to reduce the dimensionality of correlated variables in a new set of continuous variables (principal components (PCs)) that contain the most important information and explain the largest amount of variability observed in the dataset (Abdi and Williams, 2010). HCPC was used to classify trawlers into categories according to the PCs to obtain a typology that most reflects variability in environmental impacts of the vessels. Impact categories were considered active variables, and characteristics of demersal trawlers were considered descriptive variables that do not explain the dataset.

In addition to LCA impacts, we estimated other fisheries-specific impacts. Discards and fish biomass extraction were based on stock assessment and official statistics of the DGPA. Seafloor damage was estimated using the calculation method proposed by Eigaard et al. (2015).

3.2.3. Results

3.2.3.1. LCA results

The weighted mean of the abiotic depletion was 385 kg Sb eq t^{-1}, mainly from fuel and lubricating oil production (96%). Fuel and lubricating oil production contributed most (97%) to mean the ozone depletion (97% of 0.01 kg CFC-11 eq t^{-1}) and total cumulative energy demand (96% of 872,252 MJ eq t^{-1}). It was also responsible for 56% of mean land occupation (490 m^2year t^{-1}), marine eco-toxicity (6,517,908 kg 1,4-DCB eq t^{-1}) and photochemical oxidant formation (10 kg C_2H_4 eq t^{-1}). For the other impact categories, fuel and lubricating oil production was the second-largest contributor (33% of eutrophication; 29% of human toxicity; and 14% of acidification, global warming and terrestrial eco-toxicity) (Figure 3.3).

Fish production contributed most to mean acidification (84% of 639 kg SO_2 eq t^{-1}) and to global warming (81% of 56,498 kg CO_2 eq t^{-1}). Trawler and trawling net construction contributed most to mean terrestrial and human toxicity (84% and 57%, respectively) and also contributed to mean marine toxicity (31%). Paint and antifouling production contributed little to mean marine and human toxicity and land occupation (14%, 13% and 13%, respectively), while transport contributed little to all impact categories (Figure 3.3).

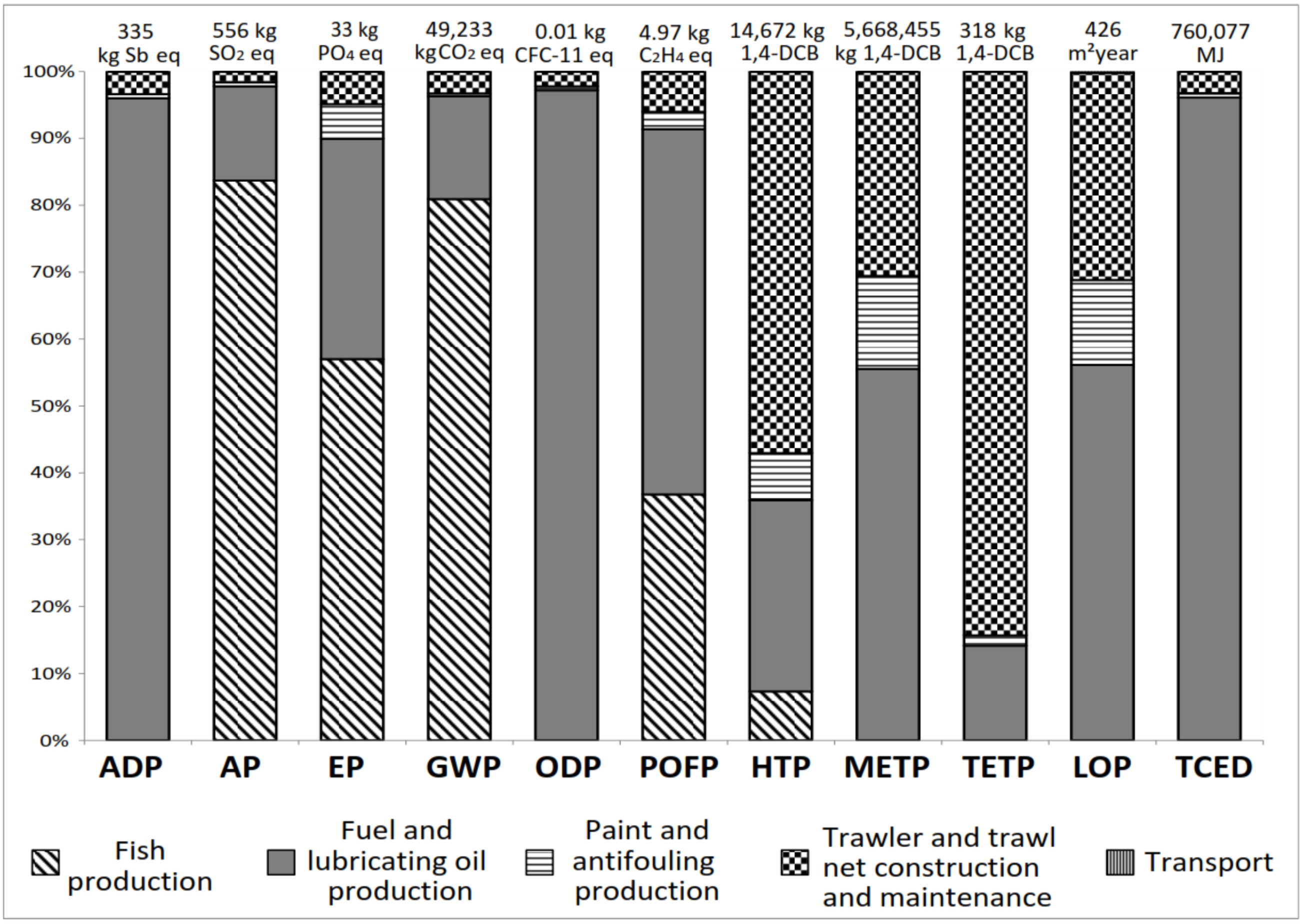

Figure 3.3 : Mean relative contribution to environmental impacts associated with demersal trawling in the Gulf of Gabes, Tunisia. ADP= Abiotic Depletion Potential, AP = Acidification Potential, EP = Eutrophication Potential, GWP = Global Warming Potential, ODP = Ozone Depletion Potential, POFP = Photochemical Oxidant Formation Potential, HTP = Human Toxicity Potential, METP = Marine Eco-Toxicity Potential, TETP = Terrestrial Eco-Toxicity Potential, LOP = Land Occupation Potential, TCED = Total Cumulative Energy Demand.

3.2.3.2. Typology and impact assessment per group

The first two PCs of the PCA explained nearly all variability (PC1 explained 99.4% and PC2 explained 0.55% of variability). PCA showed that all impact categories were strongly and positively correlated with the amount of fuel required to produce 1 t of seafood (the angle is small and close to 0°). They were strongly and negatively correlated with the annual number of fishing trips, the number of fishing trips required to land of 1 t of seafood and total annual production (the angle is close to 180°). Other vessel characteristics (e.g. length, weight, power) and their consumption of oil, antifouling and paint did not influence the intensity of environmental impacts (the angle is close to 90°)(Figure 3.4).

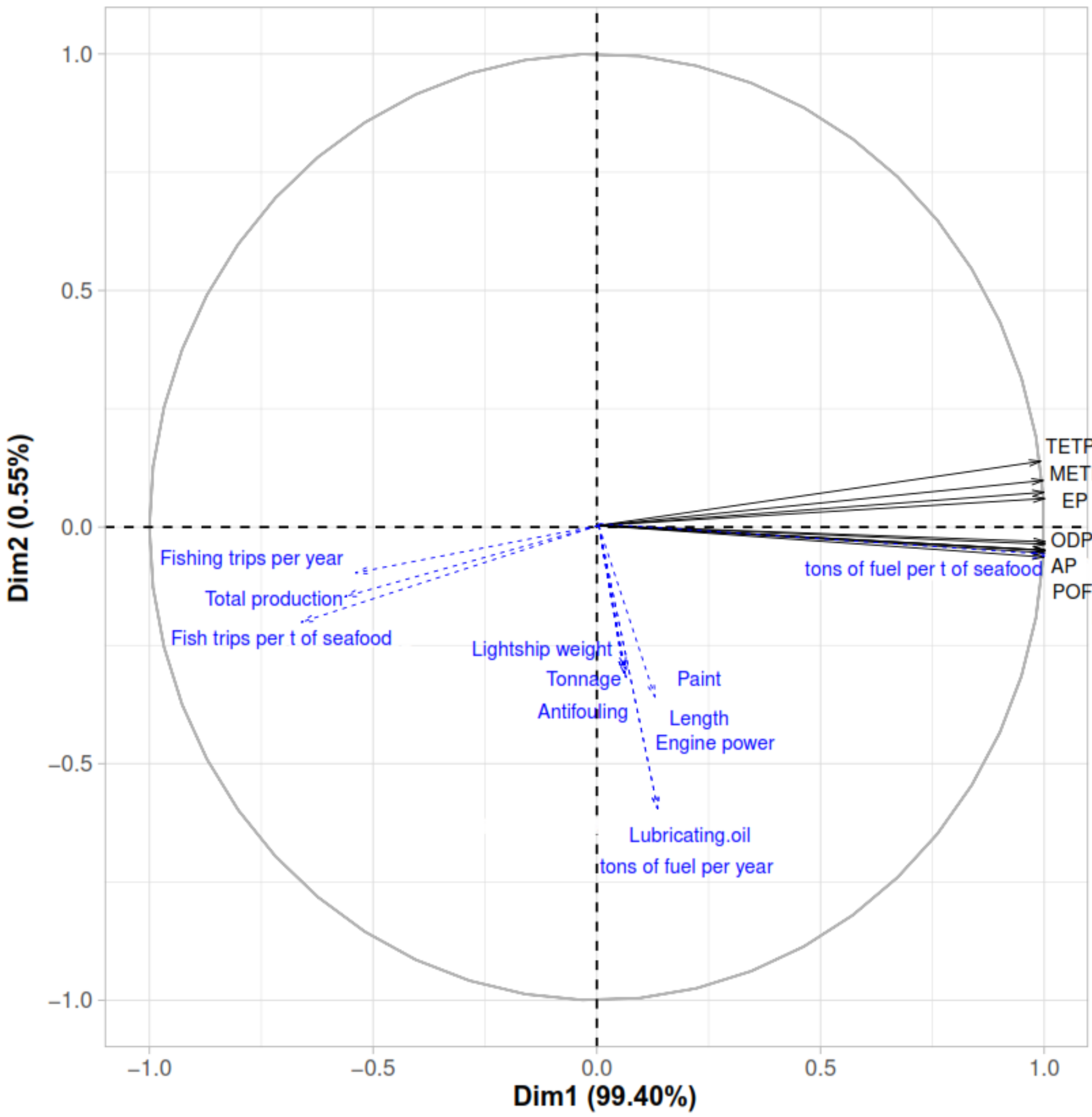

Figure 3.4 : Two-dimensional canonical graph of the variable factor map (correlation circle of the Principal Component Analysis). Variables in blue represent descriptive variables. ADP= Abiotic Depletion Potential, AP= Acidification Potential, EP= Eutrophication Potential, GWP= Global Warming Potential, ODP= Ozone Depletion Potential, POFP= Photochemical Oxidant Formation Potential, HTP= Human Toxicity Potential, METP= Marine Eco-Toxicity Potential, TETP= Terrestrial Eco-Toxicity Potential, LOP= Land Occupation Potential, TCED= Total Cumulative Energy Demand.

Then, individuals (trawlers) are spread on a two-dimensional map according to their scores on the two first two PCs. The final typology of the HCPC classified demersal trawlers into four groups based on impact intensity (Figure 3.5):

- Group 1 (G1): 130 trawlers (70% of the vessels) with low impact
- Group 2 (G2): 32 trawlers (18%) with medium impact
- Group 3 (G3): 15 trawlers (8%) with high impact
- Group 4 (G4): 7 trawlers (4%) with very high impact

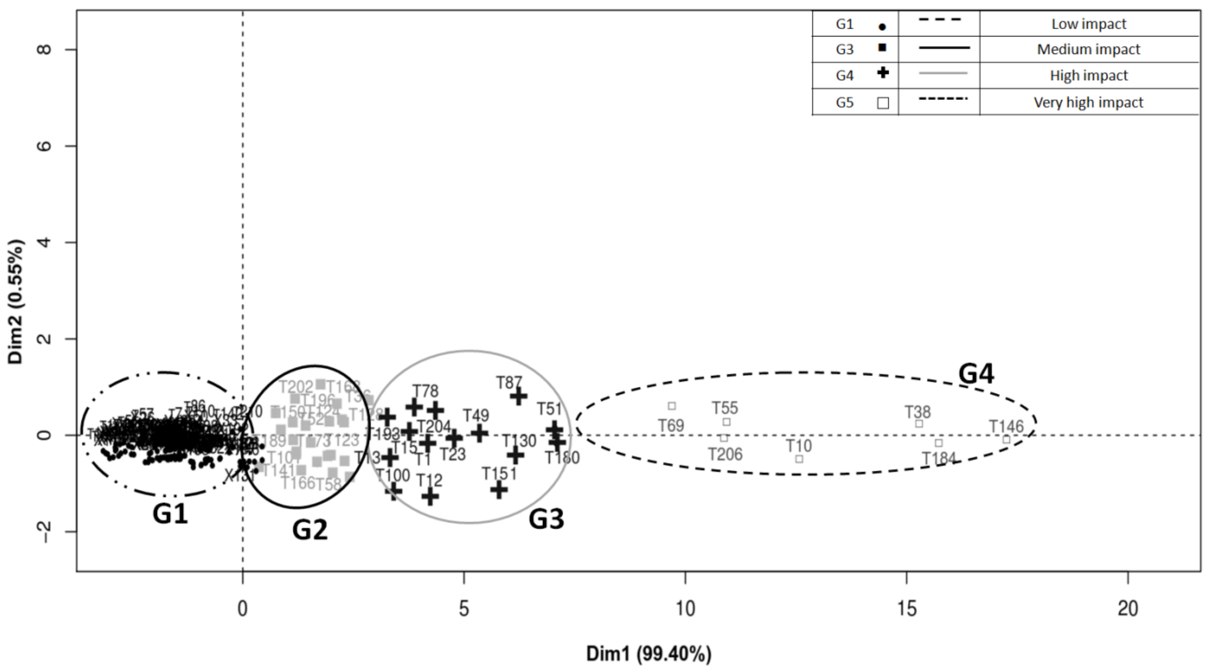

Figure 3.5 : Classification of individual wooden demersal trawlers into four groups based on Hierarchical Classification on Principal Components of the intensity of their environmental impacts.

Groups had few significant differences in trawler characteristics: e.g. mean length ranged from 23-24 m, and gross tonnage ranged from 77-86 gross tons (Figure 3.6). However, from G1 to G4, three important indicators decreased: fishing effort (25-13 fishing trips per year), catch per unit effort (1.8-0.3 t per fishing trip) and annual production (43-4 t). Compared to trawlers in G4, those in G1 had mean fishing effort twice as high, catch per unit effort 5 times as high and thus annual production 10 times as high. Mean annual fuel consumption was similar among groups, but their mean production significantly differed. As a consequence, trawlers in G1 consumed less fuel per t of seafood (3 t) than other trawlers (7, 15 and 32 t in G2, G3 and G4, respectively (Figure 3.6). Trawlers in G4 had the highest mean impact intensity for all impact categories but represented only 4% of trawlers in the Gulf of Gabes. Trawlers in G1 (70% of trawlers) had the lowest mean impact intensity. Compared to trawlers in G1, those in G2, G3 and G4 had mean impacts 2.4, 5.1 and more than 10 times as high, respectively (Table 3.1). Differences between mean impacts of all groups were significant for all impact categories (Appendix 3.2).

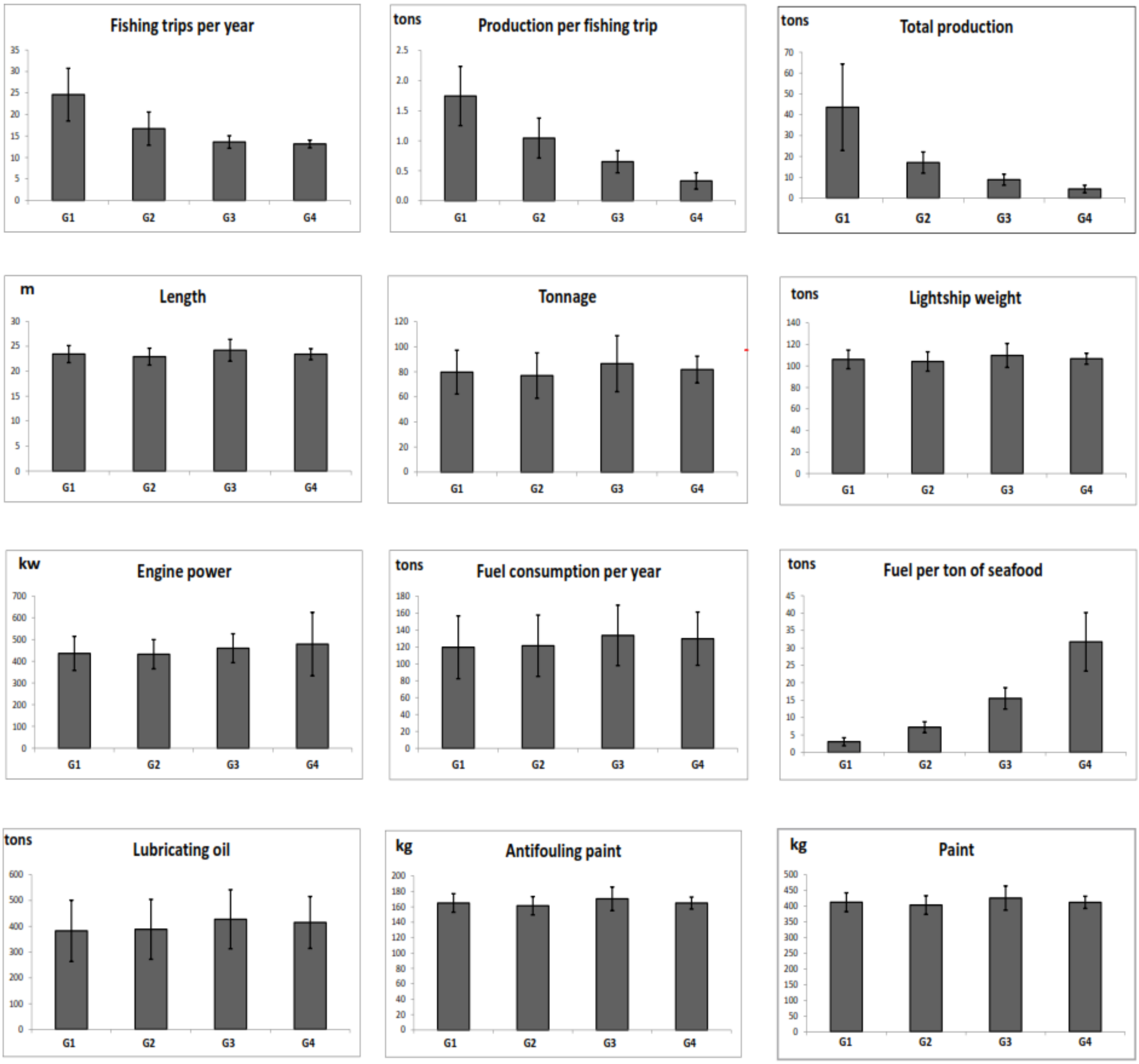

Figure 3.6 : Mean characteristics of four groups of demersal trawlers operating in the Gulf of Gabes, Tunisia. Error bars indicate standard deviations. G1: low impact, G2: medium impact, G3: high impact, G4: very high impact.

Table 3.1 : Mean environmental impacts per t of seafood landed by four groups of wooden demersal trawlers in the Gulf of Gabes, Tunisia. ADP= Abiotic Depletion Potential, AP= Acidification Potential, EP= Eutrophication Potential, GWP= Global Warming Potential, ODP= Ozone Depletion Potential, POFP= Photochemical Oxidant Formation Potential, HTP= Human Toxicity Potential, METP= Marine Eco-Toxicity Potential, TETP= Terrestrial Eco-Toxicity Potential, LOP= Land Occupation Potential, TCED= Total Cumulative Energy Demand. G1: low impact, G2: medium impact, G3: high impact, G4: very high impact.

Impact category	Unit	G1		G2		G3		G4		Weighted mean
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	
ADP	kg Sb	81	34	194	34	415	78	849	191	385
EP	kg PO_4	8	3	19	3	41	8	84	18	38
AP	kg SO_2	135	57	321	57	689	130	1,409	318	639
GWP	kg CO_2	11,996	5,045	28,475	5,090	60,937	11,516	124,585	28,067	56,498
ODP	kg CFC-11	0.002	0.001	0.005	0.001	0.011	0.002	0.023	0.005	0.01
POFP	kg C_2H_4	2	0.7	5	1	10	2	21	6	10
HTP	kg 1,4-DCB	3,651	1,538	8,615	1,691	18,211	4,308	37,043	7;294	16,880
METP	kg 1,4-DCB	1,404,864	583,232	3,320,861	611,042	7,041,896	1,513,465	14,304,012	3,005,231	6,517,908
TETP	kg 1,4-DCB	80	34	187	40	395	104	805	146	367
LOP	m^2year	106	44	251	46	530	117	1,074	229	490
TCED	MJ	185,233	77,872	439,683	78,572	940,812	177,709	1,923,281	433,359	872,252

3.2.4. Discussion

Environmental impacts associated with demersal trawling are linked mainly to onboard activities of the trawlers (mainly AP and GWP) and to production of fuel and lubricating oil (mainly METP and TCED). This is consistent with previous fishery impact assessment studies and results of studies that identified fish harvesting activities as contributing most to most impact categories (Ziegler et al., 2003; Thrane, 2004; Tyedmers, 2004; Hospido and Tyedmers, 2005; Pelletier et al., 2007; Schau et al., 2009; Vázquez-Rowe et al., 2011a, 2012b). As previously found in many fisheries LCA, fuel production and fuel combustion (included in the fish production stage) contributed most to most impact categories (Avadí and Fréon, 2013b). The large contribution of fishing operations and fuel production to most impacts is due to operational issues related to the fishing gear used, which directly influences energy efficiency (Avadí and Fréon, 2013b; Thrane, 2004; Vázquez-Rowe et al., 2011a). Demersal trawling methods are the most fuel-intensive (Avadí and Fréon, 2013b; Schau et al., 2009).

Construction of vessels and trawling nets contributes greatly to HTP, less to METP and LOP and little to the other impact categories. Most LCA fishery studies exclude construction from analysis because it tends to contribute little to environmental impacts (Avadí and Fréon, 2013b; Ziegler et al., 2003). Paint and antifouling production contributes little to most impact categories, but its contribution to HTP and METP is large due to xylene, copper and zinc oxide emissions. Transport contributes little to impacts; thus, it is not a key subsystem to include in LCA of Tunisian demersal trawling.

Results from this study can help stakeholders identify operational inputs that must be optimized to implement cleaner production strategies. Management practices of demersal trawling vessels could be improved based on the hotspots identified. In Tunisia, groups of trawling vessels with high and very high environmental impacts used more fuel to land 1 t of seafood (15.2 and 29.8 t for G3 and G4, respectively). Therefore, actions for improvement must focus on reducing fuel consumption (Vázquez-Rowe et al., 2011a). Ultimately, fuel consumption per ton landed (or another FU) of trawling vessels operating in the Gulf of Gabes ecosystem is influenced by multiple factors. The main factor is likely the trawler's specialization, i.e. the species, fishing zone and gear it chooses. In particular, the abundance of the stocks targeted, partially related to their status, is a key factor in determining the catch per unit effort and thus the yearly production of each vessel. In our study, we did not have enough data on vessel activities to identify specializations. However, we know that demersal trawlers in the Gulf of Gabes target demersal finfish or shrimp, especially depending on the season. The relative importance of these two specializations during the year might explain, at least partially, the contrasts observed among the four vessel groups. In particular, low production per fishing trip seems characteristic of shrimp fisheries. This implies that the larger impacts identified in the LCA come from vessels that usually target shrimp throughout the year, some fishing only a few days per year, and in all cases consuming large amounts of fuel to land only a few tons (albeit with high value). In contrast, vessels targeting finfish use less fuel per t of seafood landed because they target larger stocks. Thus, these vessels spend less time and fewer resources to catch similar amounts.

Another important factor is the “skipper effect” (Vázquez-Rowe and Tyedmers, 2012), which depends on the skills and experience of the vessel crew. Using electronic methods to select the fishing grounds rather than relying on word of mouth, as is currently practiced, could improve the performance of trawling vessels and consequently their environmental performance. Another improvement that stakeholders could encourage is to change the shape of the hull, which can increase energy efficiency up to 20% (Schau et al., 2009), and changing engine technology to electronic fuel injection engines to improve combustion and reduce fuel consumption (Woodyard, 2009). Emissions from fuel consumption depend on the quality of the fuel itself. Therefore, it is beneficial to replace fossil fuels with fuels (biofuels) that can decrease CO_2 emissions. Another action stakeholders could take to decrease fuel consumption is to encourage pelagic trawling instead of demersal trawling since the former is less fuel-intensive (Schau et al., 2009; Thrane, 2004). However, each type of trawling targets different stocks; thus, considering this action requires caution due to its potential socio-economic impacts.

In addition to demersal trawling’s direct negative impacts, it also has several indirect impacts. As a non-selective fishing activity, demersal trawling results in large amounts of discards: it is responsible for 50% of discards worldwide and lands only 22% of catches (Kelleher, 2005). The DGPA official statistics showed that total landings of seafood were 23% lower than those reached in early 1990s. Catches declined from 65,845 t in 1988 to 40,847 t in 1995. By the end of the 2000s, total catches reached 40,000 t, representing 40% of the total seafood production in Tunisia. This decrease is due to fisheries exceeding maximum sustainable yield for most exploited species (Missaoui et al., 2001). Discards related to bottom trawling activity exceeds 50%. In fact, to produce 1 kg of seafood by bottom trawling, 2.7 kg of small fish is being discarded and the quantity of discard per hour is estimated to 73 kg (Jarboui et al., 2005). Demersal trawling also results in extensive damage to the seafloor (Thrane, 2006). The average damage resulted from bottom trawlers in the Gulf of Gabes on seafloor is equal to 1.35 $km^2.h^{-1}$. This damage is higher than the one estimated for otter trawling for Nephrops and mixed demersal fish (1.2 $km^2.h^{-1}$). Among paint and antifouling paint ingredients, copper oxide is responsible for most toxicity. Antifouling paint with high copper concentrations has already replaced tributyltin (TBT) compounds, which were banned in 1999 by the International Maritime Organization (IMO, 2008).

Comparing results of fisheries LCAs is challenging due to methodological differences among them (Henriksson et al., 2012). Thus, it is not possible to compare environmental impacts of seafood products accurately using published results. Nevertheless, previous studies provide valuable conclusions, such as concluding that fuel consumption and the use of paint and antifouling paint contribute most to environmental impacts. Environmental impacts of vessels in our study are similar to those of (Vázquez-Rowe et al., 2012c) and Ziegler et al. (2011). Galician (NW Spain) offshore trawlers (Vázquez-Rowe et al., 2012c) had lower ADP (51.4 kg Sb eq t^{-1}), AP (115 kg SO_2 eq t^{-1}) and GWP (8759 kg CO_2 eq t^{-1}) than all trawlers in the Gulf of Gabes. They had higher ODP (0.0172 kg CFC-11 eq t^{-1}) than trawlers in G1, G2 and G3 (i.e. higher than that of 96% of all trawlers). They also had higher EP (21 kg PO_4 eq t^{-1}) than trawlers in G1 and G2 (i.e. higher than that of 78% of all trawlers), mainly because they had higher energy use efficiency than trawlers in the Gulf of Gabes.

Mauritanian trawlers targeting pink shrimp (Ziegler et al., 2011) had higher ODP (0.27 kg CFC-11 eq t^{-1}), lower POFP (1.42 kg C_2H_4 eq t^{-1}) and lower HTP (1760 kg 1,4-DCB eq t^{-1}) than all trawlers in the Gulf of Gabes. They had higher AP (286 kg SO_2 eq t^{-1}) and TCED (452,000 MJ eq t^{-1}) than trawlers in G1 and G2 (i.e. higher than those of 78% of all trawlers). They also had higher GWP (35,000 kg CO_2 eq t^{-1}) than trawlers in G1 and G2 and higher EP

(45.4 kg PO_4 eq t^{-1}) than trawlers in G1, G2 and G3. This is because the trawlers in Ziegler et al. (2011) targeted mainly pink shrimp, making them less fuel efficient per FU.

Mean environmental impacts per group showed high standard deviations for all impact categories (Table 3.1), related mainly to differences in vessel characteristics in each group and to onboard vessel activities. Along with issues inherent to LCA itself, fishery LCAs encounter additional unresolved challenges. Most challenges are related to the absence of standardized fishery-specific impact categories that consider the influence of technological, spatial and temporal variability of fishing on fuel consumption. This study could be improved by combining LCA results with geographic information systems to track vessel trips and by including impact categories related to the direct impact of fishing on stock abundance, the seafloor, food webs or marine biodiversity. Including updated data on stock distribution and abundance would allow for better understanding of interactions between fishery management practices and the ecological, operational and economic aspects of the activity. Another interesting development would be to extend the length of the assessment period to assess the effect of seafood stock abundance on the efficiency of demersal trawling in the Gulf of Gabes. However, the data available to perform this case study did not allow for a more complete LCA, which would provide a more accurate assessment of demersal trawlers.

The current study would be improved by extending the boundaries to include post-harvesting processes related to demersal trawling. It would be useful to increase the timeframe and consider the spatial dimensions of analysis since the system's large temporal and spatial variability yields large variability in environmental impacts. Conducting LCA of other fishing fleets in the world may help to develop policies for integrated fishing management and encourage the use of fishing methods that are less harmful than demersal trawling. Due to the rapid expansion of aquaculture, it is important to compare the economic, social and environmental performance of both sectors to assess the appropriateness of shifting from fisheries to aquaculture. It is also important to consider the impacts that aquaculture diversification (reared species) has on demersal trawling.

3.2.5. Conclusion

To our knowledge, this is the first fishery LCA study in the southern Mediterranean and is one of the few conducted worldwide. Using the Gulf of Gabes as a case study, it provides comprehensive assessment of environmental performance associated with the landing of 1 t of seafood by demersal trawlers. Classifying demersal trawlers into groups based on their impact intensity highlights huge contrasts among groups. Results indicate that impact intensity is directly proportional to the amount of fuel consumed to land 1 t of seafood. Based on this analysis, we conclude that onboard vessel activities, and especially the specialization chosen, contribute most to environmental impacts. This is due mainly to the low production of certain specializations, such as shrimp trawling, which has high energy consumption. Fuel production and antifouling paint production also contribute to the impacts. Therefore, efforts to improve the environmental performance of demersal trawling operations must focus on minimizing fuel consumption per t landed, promote the most productive specializations, increase fuel efficiency and replace toxic substances in antifouling paint with less harmful compounds. The multicriteria approach of LCA provides useful assessment of the environmental performance of demersal trawling. However, analysis could be improved by including impacts related to biodiversity and impacts on the ecosystem. Including biological and fishery-specific impacts is also important; examples include discards, impacts on the seafloor and marine communities, along with impact categories that identify interactions between environmental, economic and social aspects.

3.3. Manuscrit D "Combining ecosystem indicators and life cycle assessment for environmental assessment of demersal trawling in Tunisia"

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Abstract

The present study assesses environmental performance of seafood production by demersal trawling in Tunisia (Gulf of Gabes). Ecosystem quality indicators were determined using an ecosystem modeling tool, Ecopath with Ecosim (EwE), and were combined with life cycle assessment (LCA) to increase the relevance of both tools' assessments when applied to fisheries. We simulated several management plans and assessed their influence on environmental performance and characteristics of the ecosystem. The approach consisted of conducting LCA and calculating ecosystem indicators to provide a complete assessment of trawling's environmental impacts and the ecosystem characteristics associated with seafood production. The functional unit for the LCA was set to 1 t of landed seafood, and system boundaries included several operational stages related to demersal trawling. End-of-life and post-landing stages were not considered in the analysis due to lack of reliable data. Ecosystem indicators from EwE include the primary production required (PPR), PPR/catch, PPR of demersal trawlers, PPR/catch of demersal trawlers, total yield, demersal trawler yield, marine trophic index, apex predator indicator, the trophic level of catches, and biomass of keystone groups. Demersal trawling in the exploited ecosystem of the Gulf of Gabes (southern Tunisia) was used as a case study to illustrate the applicability of the approach. Ecospace, the spatial module of EwE, was used to simulate management scenarios: establishment of marine protected areas, extension of the biological rest period, and decrease in the number of demersal trawlers. LCA revealed that production of fish, fuel/lubricating oil, and paint/antifouling contributed most to environmental impacts. All management plans simulated decreased environmental impacts compared to the baseline scenario. The most effective management plan is extending the rest period, which increases demersal trawler yield and greatly decreases the PPR/catch of demersal trawlers. The method developed in this study is relevant for supplementing LCA of fisheries and potentially that of seafood production systems. It provides policy makers with practical information to help implement effective management plans in the context of an ecosystem approach to fisheries.

Keywords: Life Cycle Assessment, Ecosystem modeling, Ecopath with Ecosim, Ecospace, Demersal trawling, Environmental impacts, Gulf of Gabes.

3.3.1. Introduction

Seafood products represent more than 9% of the economic value of total agricultural exports and 1% of that of world merchandise trade (FAO, 2016). The seafood trade has substantially expanded over the past few decades and is fueled by the increase in world demand for seafood, from 9.9 kg per capita in the 1960s to 19.7 kg in 2013, with preliminary estimates rising above 20 kg per capita in 2015 (FAO, 2016). Seafood represents about 17% of the global population's intake of animal protein and 6.7% of all protein consumed (FAO, 2016). Since the Industrial Revolution, fishing activity has expanded considerably in terms of fishing effort and the number of fishing units and fishing grounds, because fisheries operate in an increasingly globalized environment (Pauly et al., 2002; Swartz et al., 2010). On a global scale, marine fishery production increased to 86 million t in 1996 but slightly decreased recently due to the overexploitation of several fish stocks (FAO, 2016). Compared to agriculture, the global seafood economic system is relatively small; however, the increased supply of seafood carries the risk of ecological degradation of ecosystems and has considerable impact on the world's environment (Kaiser and de Groot, 2000, p. 200). Therefore, it is imperative to apply sustainability principles to seafood production systems.

Long-term sustainability of fishing is a major concern from an environmental and ecological viewpoint. Fishing activity carries the risk of negative direct and indirect impacts on marine ecosystems (Kaiser and de Groot, 2000), mainly because it relies entirely on extracting organisms from the ecosystem (Christensen et al., 2003). Consequently, environmental impacts of seafood production have been intensively studied in recent decades (World Bank, 2017; Worm et al., 2009). However, most environmental analysis focused on the immediate impact of fisheries on targeted stocks (Costello et al., 2016), by-catch and discards (Glass, 2000), benthic communities (Guyonnet et al., 2008), seabed damage (Kaiser et al., 2006) and changes in trophic dynamics, and the structure and functioning of the ecosystem (Jackson et al., 2001; Pauly et al., 2002; Tremblay-Boyer et al., 2011).

An integrated, science-based approach is important for impact assessment, and life cycle assessment (LCA) is an effective method that considers the entire supply chain to estimate potential environmental impacts associated with seafood production (Pelletier et al., 2007). Since the 2000s, LCA has been applied to fisheries around the world (Tyedmers, 2000; Ziegler et al., 2003, 2011; Hospido and Tyedmers, 2005; Iribarren et al., 2010; Vázquez-Rowe et al., 2010, 2012b; Ramos et al., 2011; Fréon et al., 2014; Avadí et al., 2015). Although LCA is an extensive approach, given the range of impacts it is able to assess, authors of most seafood LCA studies have strongly recommended including ecosystem components (e.g. biotic resources, primary production, trophic interactions) to supplement the impact assessment (Avadí and Fréon, 2013b), especially with the current overexploitation of marine resources and increased disturbances in marine ecosystems caused by human activities (Halpern et al., 2008). Several LCA studies included and discussed direct fishery-specific impacts, most of which were calculated outside the LCA framework (Avadí and Fréon, 2013b). For example, Langlois et al. (2014a) developed a biotic resource use impact category to quantify the amount of biotic biomass removed by fishing activity. Biotic resource use includes estimates of the Primary Production Required (PPR). The sea-use impact category was also introduced in LCA to represent physical impacts due to occupation or transformation of marine areas (Langlois et al., 2014b). The lost potential yield impact category was developed to quantify overfishing and the depletion of exploited fish stocks (Emanuelsson et al., 2014). Specific discard indexes in LCA were developed to characterize and standardize estimates of discards in fisheries (Vázquez-Rowe et al., 2012c).

Ecosystem models are used in ecosystem-based fishery management to maintain the sustainability, health, productivity, and resilience of ecosystems. Ecopath with Ecosim (EwE, Christensen and Walters, 2004) is one of the most frequently used models in the world to model marine and aquatic ecosystems (Plagányi, 2007). The model provides better understanding of impacts of fishing on target and non-target species and assesses interactions between ecosystem components. The EwE approach explicitly considers trophic interactions and helps in studying fishing activities within an ecosystem context. EwE has three main modules: (i) Ecopath, a static mass-balanced snapshot of the system; (ii) Ecosim, a dynamic simulation module; and (iii) Ecospace, a spatial and temporal dynamic module.

EwE provides valuable information about ecosystem functioning; however, it considers only extraction of organisms from the ecosystem by fisheries and overlooks relevant aspects related to the performance of fishing, (e.g. fuel consumption (Thrane, 2004; Tyedmers et al., 2005)). The model does not consider effects of the energy and material used to construct and maintain fishing vessels and gear (Hayman et al., 2000; Ziegler et al., 2003) and the use of paint and antifouling paint (Hospido and Tyedmers, 2005). LCA considers these aspects, which are crucial to establish a robust and complete impact assessment of fishing.

Located in southern Tunisia, the Gulf of Gabes is a major fishing ground with great economic and ecological importance. It is considered one of the most productive areas in the Mediterranean Sea in terms of catches (Halouani et al., 2015b; Papaconstantinou and Farrugio, 2000). The Gulf of Gabes supports 60% of fleets in the country and provides more than 40% (more than 40,000 t) of the annual national fish production (DGPA, 2015). Catches are dominated by Sparidae (e.g., Diplodus annularis), mullet (Mullus barbatus and M.

surmuletus), round sardinella (Sardinella aurita), European pilchard (Sardina pilchardus) and several benthic cephalopods (e.g. Sepia officinalis, Octopus vulgaris). Demersal trawling is the dominant fishing gear in the Gulf of Gabes (Hattab et al., 2013; Mosbah et al., 2013) and is considered the most destructive fishing gear worldwide. It damages bottom habitats and harms benthic communities, in addition to its non-selectivity (Kumar and Deepthi, 2006). Expansion of fisheries resulted in overexploitation of several stocks (Fiorentino et al., 2008). One sign of overexploitation in the Gulf of Gabes is a decrease in hourly yield from 75 kg h^{-1} in the 1970s to 30 kg h^{-1} in the 1990s. To address these issues, the EwE model was applied to the Gulf of Gabes. The mass-balance model was developed to better understand ecosystem structure and functioning and to study impacts of fisheries (Hattab et al., 2013). In addition, the Ecospace module was used to investigate potential ecosystem responses to spatial and temporal management plans (Abdou et al., 2016).

LCA of demersal trawlers and EwE in the Gulf of Gabes were developed separately and published previously (Abdou et al., 2018; Hattab et al., 2013). Combining EwE with fish supply-chain models was previously attempted (Avadí et al., 2014). The ultimate goal of this study is to develop a new set of potential indexes from EwE to supplement seafood LCA studies and place them in an ecosystem context. The method was applied to the Gulf of Gabes ecosystem. In addition, EwE was used to assess potential ecosystem responses to different management scenarios.

3.3.2. Materials and methods

3.3.2.1. Study area: the Gulf of Gabes

The Gulf of Gabes is located in the southern Mediterranean Sea and covers approximately 35,900 km^2 (Figure 3.7). The gulf is characterized by its wide continental shelf (a depth of 200 m is not reached until 400 km offshore), resulting in high sensitivity to atmospheric changes (Natale et al., 2006). It has the highest tidal amplitude in the Mediterranean Sea, reaching 1.8 m in height (Sammari et al., 2006). The gulf contains a large bed of Posidonia oceanica, an endemic Mediterranean seagrass (Batisse and Jeudy de Grissac, 1998) that provides an important nursery, feeding and breeding ground for many marine species (Hattour, 1991). The Gulf of Gabes is under multiple natural and anthropogenic threats (Ben Rais Lasram et al., 2015a; Lamon et al., 2014). It is a major fishing ground in Tunisia due to its richness in benthic fauna (i.e. shrimp, mullets, soles) and the presence of soft bottom habitats that facilitate access to resources (Missaoui et al., 2000). Demersal trawling is the predominant fishing activity in the gulf (Mosbah et al., 2013). Based on Tunisian Fisheries and Aquaculture Department (DGPA) statistics, the number of demersal trawlers increased to 285 from 1980-1991 and decreased to 229 in 1997. The number of trawlers has fluctuated around 250 since 1997 (DGPA, 2015). In 2015, 226 demersal trawlers were operating in the gulf, and most (184) were wooden (DGPA, 2015) targeting shrimp and demersal finfish (Sparidae (*D. annularis*, *Sparus aurata*), mullets, rays (*Raja clavata*), and sharks (*Mustelus mustelus*). Demersal trawlers in the Gulf of Gabes produced 10,332 t of seafood in 2015, which generated approximately 41 million € (DGPA, 2015). The Gulf of Gabes is an archetypal ecosystem in which the effects of fisheries are the most pronounced, and according to stock assessments, is considered a highly exploited ecosystem. Therefore, it is necessary to establish adequate management practices to facilitate the recovery of marine resources.

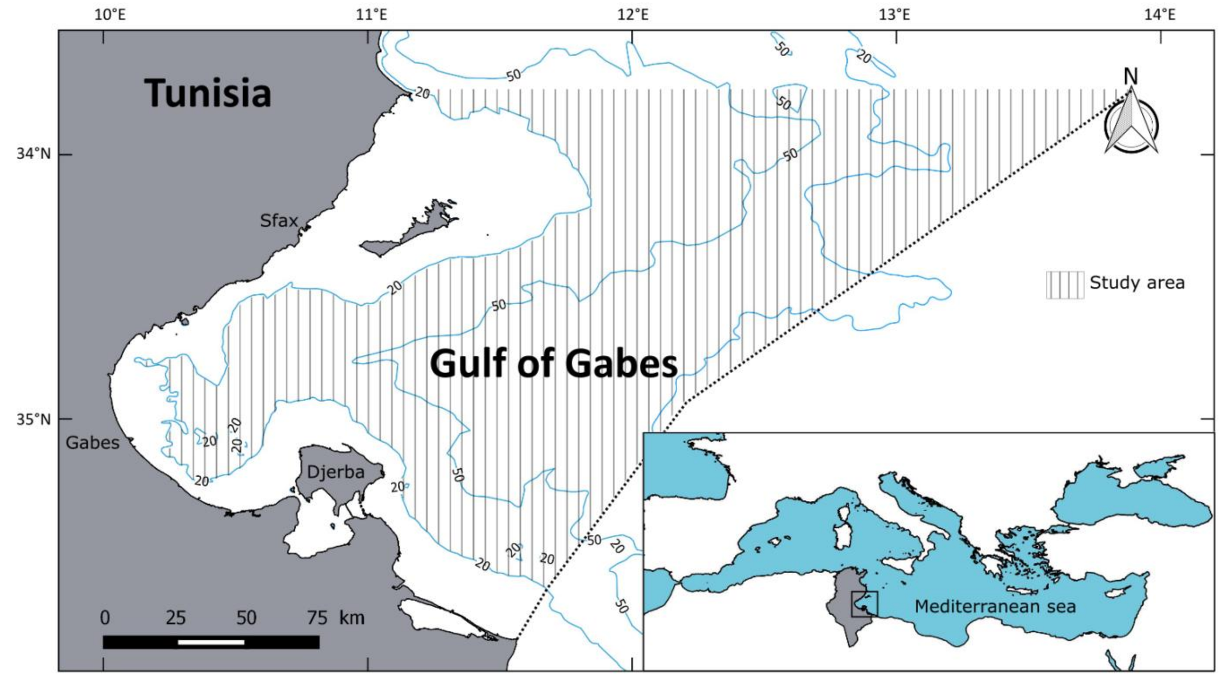


Figure 3.7 : Geographic location of the study area in the Gulf of Gabes ecosystem.

3.3.2.2. Life cycle assessment

LCA is a robust standardized method (ISO 14040) (ISO, 2006a, 2006b) to estimate potential environmental impacts associated with a product or a service throughout its entire life cycle, "from cradle-to-grave", i.e. from the extraction of raw materials through production, construction, use, and waste management and disposal or recycling (Consoli et al., 1993; Guinée et al., 2002). Based on the International Reference Life Cycle Data System (European Commission, 2010) recommendation, LCA is performed following four steps:

- Goal and scope definition: an explicit statement of the goal and the scope of the study. It is necessary to define the functional unit (FU, the reference unit in which impacts are reported). System boundaries are defined and distinguish which processes are included in the study. Assumptions and limitations are identified.
- Life cycle inventory (LCI): LCA requires a broad data inventory to reflect the complexity of the production system. Flows from and into the environment involved in producing the FU are considered. The LCI includes inputs of energy and raw materials and outputs released to the air, land, and water. Input and output data required to construct the model are collected for all activities within the system boundary and are then related to the FU.
- Life cycle impact assessment (LCIA): Environmental impacts related to production are estimated based on the LCI. LCIA requires selecting impact categories that reflect the environmental issues described in the goal and scope.
- Interpretation: LCIA results are summarized, verified and assessed.

The present study was based on a seafood LCA of demersal trawlers in Tunisia as case study (Abdou et al., 2018) which quantified environmental impacts associated with landing seafood caught by wooden demersal trawlers in the Gulf of Gabes. The FU was set as 1 t of landed seafood. Of the 226 demersal trawlers in the Gulf of Gabes, the 184 wooden vessels were selected for this study. The studied system covers a wide range of operational stages related to demersal trawling (i.e. seafood production, trawler and trawl net construction and maintenance, paint and antifouling paint production, fuel and lubricating oil production, and transport). However, end-of-life stages (e.g. material recycling, disposal of certain materials) and post-landing stages (e.g. sorting and packaging, sale, use and processing) were excluded from the analysis due to lack of reliable data.

The LCI was based on data collected from official DGPA records (e.g. landings, length, tonnage, engine type, engine power, lightship weight). Additional data were obtained from surveys of demersal trawler skippers and fishermen in the port of Sfax, the main fishing port in the Gulf of Gabes, and of demersal trawler builders in the shipyard. Collected data supplement and validate official statistics (see Abdou et al. (2018) for further details about the method). To estimate impacts, data were aggregated into 11 of the most commonly used impact categories based on previous guidelines in fishery LCA studies (Avadí and Fréon, 2013b). Impacts were calculated per t of seafood produced following the CML2 baseline 2000 method using SimaPro® 8.0 software (Goedkoop et al., 2008). The following impact categories were included:

- Abiotic Depletion Potential: reflects the decrease in non-renewable and renewable abiotic resources available for human use; expressed in kg Sb equivalent (eq).
- Acidification Potential: reflects negative acidic effects on water and soil generated by production; expressed in kg SO_2 eq.
- Eutrophication Potential: represents negative effects of discharging nitrogen and phosphorus into the environment; expressed in kg PO_4 eq.
- Global Warming Potential: represents effects of greenhouse gas emissions on climate change; expressed in kg CO_2 eq.
- Ozone Depletion Potential: represents potential damage to the ozone layer caused by chlorinated and brominated chemicals; expressed in kg CFC-11.
- Photochemical Oxidant Formation Potential: represents negative effects of chemical substances caused by sunlight reacting with emissions from reactive substances (fossil fuel); expressed in kg ethylene (C_2H_4) eq.
- Human Toxicity Potential: represents potential harm of a unit of chemical released into water, air or soil; expressed in kg 1,4-dichlorobenzene (1,4-DCB) eq.
- Marine Ecotoxicity Potential: represents negative effects of toxic substances on marine ecosystems; expressed in kg 1,4-DCB eq.
- Terrestrial Ecotoxicity Potential: represents the negative impacts of toxic substances on terrestrial ecosystems; expressed in kg 1,4-DCB eq.
- Land Occupation Potential: represents the land area necessary to produce the FU (1 t of seafood); expressed in m^2year.

- Total Cumulative Energy Demand: represents the amount of energy (e.g. fossil fuels, electricity) necessary to produce the FU (1 t of seafood); expressed in megajoules (MJ).

A full description of the LCI and impact categories are found in Abdou et al. (2018). All impact categories were calculated for an average demersal trawler in the Gulf of Gabes.

3.3.2.3. Ecopath with Ecosim model

Principles, basic concepts and assumptions of the EwE modeling approach are described in detail in Christensen et al. (2008); Christensen and Walters, (2004); Walters et al. (1997). EwE has three main components:

- Ecopath: a static snapshot of interactions among functional groups in an ecosystem (Christensen and Walters, 2004). Ecopath is built from two linear equations: one for mass balance and one for energy balance.
- Ecosim: a dynamic simulation model based on balanced Ecopath parameters. It enables exploring effects of fishing options and changes in ecosystem functioning (Christensen and Walters, 2004).
- Ecospace: a spatially explicit dynamic module of EwE (www.ecopath.org; Christensen and Walters, 2004; Walters et al. 1999). It integrates trophic and temporal dynamics of Ecopath and Ecosim in a two-dimensional space. After spatial grid cells are defined, each cell is assigned a habitat type, which has a relative primary production (Christensen et al., 2008). Each functional group is assigned to its preferred habitat type, and each type of fishery is assigned to its allowed fishing zones (Walters et al., 1999).

Ecopath includes indicators that describe the ecosystem based on information about the food web, trophic flow, thermodynamic concept, information theory, and network analysis (Christensen and Walters, 2004; Coll et al., 2006). Fishing activities can influence the maturity, stability, and complexity of ecosystems on several levels. Indictors in EwE models indicate the state of the ecosystem and how it changes over time (Christensen and Walters, 2004).

In the present study, the following indicators from the EwE model were chosen to supplement LCA and place its results in an ecosystem context:

Pressure indicators:

- PPR: Ecopath estimates PPR by removing all cycles from the diet composition (DC') and identifying all paths in the flow network using the method of Ulanowicz (1995). PPR of yield Y of a given group of species is quantified by summing all pathways leading to the group: $PPR = \sum_{paths}[Y.\prod_{pred,prey}\frac{Q_{pred}}{P_{pred}}.DC'_{pred,prey}]$, where $\frac{Q_{pred}}{P_{pred}}$ is the consumption:production ratio. PPR, which is equivalent to Net Primary Production, enables ecosystems, including terrestrial ecosystems to be compared. Many authors have developed methods to calculate it, and the one most frequently used is (Pauly and Christensen, 1995): $PPR = \sum_{i=1}^{n}\frac{Y_i}{CR}.\left(\frac{1}{TE}\right)^{(TL_i-1)}$, where Y_i 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 and was assumed to be 10%, TL_i is the trophic level of species i and n is the number of species caught. In this study we used the PPR calculated by EwE. We also calculated PPR/catch, PPR of demersal trawlers and PPR/catches of demersal trawlers.
- Yield: yields in Ecopath are expressed in t $year^{-1}$ km^{-2}.

Exploited resources indicators

- Mean trophic index (MTI): describes direct and indirect trophic interactions among functional groups (Pauly and Watson, 2005). It equals $\frac{\sum TL_i.B_i}{\sum B_i}$, where B is the biomass of species i. For this indicator to be sensitive to fishing pressure, only species with a trophic level higher than 3.25 (a standard threshold) are considered; species of low trophic level are excluded because their biomass tends to vary greatly in response to environmental factors (Pauly and Watson, 2005).
- Mean trophic level of the catch (TLc): reflects effects of fishing on the food web (Pauly et al., 1998). It is calculated as: $TLc = \frac{\sum TL_i.Y_i}{\sum Y_i}$.

Trophic chain indicators

- Mean trophic transfer efficiency (TE): the percentage of prey production that is transferred to predator production. It equals predator production divided by prey production.
- Apex predator indicator (API): the percentage of predators with a trophic level higher than 4 (top predators) out of all predators, excluding planktivores (i.e. trophic level < 3.25) (Bourdaud et al., 2016). Fishing decreases API by removing large individuals of high trophic level.

Specific biodiversity indicators

- Biomass of keystone groups: these are groups that have an important structuring function in the food web despite their relatively low biomass (Power et al., 1996). Keystone species are able to influence ecosystem dynamics and can strongly influence the abundance of other groups (Piraino et al., 2002). Thus, it is important to identify these groups to maintain ecosystem integrity and biological diversity (Tilman, 2000). Ecopath uses the approach of Libralato et al. (2006) to identify keystone species by plotting the “keystoneness” of each group $\mathrm{i}\ (\mathrm{KS_i}) = \log[\varepsilon_\mathrm{i}(1-\mathrm{p_i})]$, where ε_i is the overall impact, and $\mathrm{p_i}$ is the relative biomass of the group, excluding detritus biomass.

This study is based on the EwE model of Hattab et al. (2013) and the Ecospace model of Abdou et al. (2016). The EwE model for the Gulf of Gabes was created with EwE version 6.2 (www.ecopath.org; Christensen and Walters, 2004; Walters et al. 1999). The model includes 62 species divided into 41 functional groups based on ecological and taxonomic similarities. It includes the main fleets operating in the area: demersal trawling, small seines, tuna purse seines, purse seines using lights, coastal motorized fishing, and sponge fishing. Landing statistics were obtained from DGPA. Further details of data resources and parameterization are found in Hattab et al. (2013).

Landing data were collected by the Tunisian National Institute of Sciences and Technologies of the Sea. Ecosim was fitted to landings for the period 1995–2008, time series of fishing effort by fishing fleet, and stock assessment estimates of functional group biomass. In addition, primary production in the study area for the period 1997–2007 (data from SeaWIFS project, http://oceancolor.gsfc.nasa.gov/SeaWiFS/) was used to calibrate Ecosim (Halouani et al., 2013).

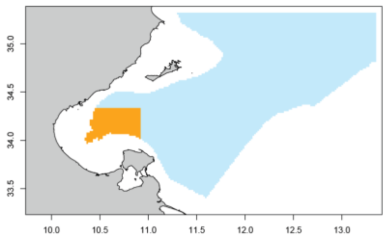
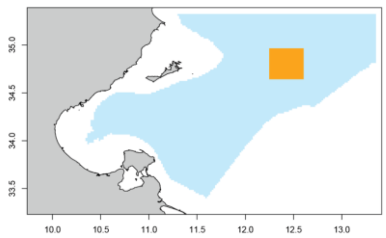
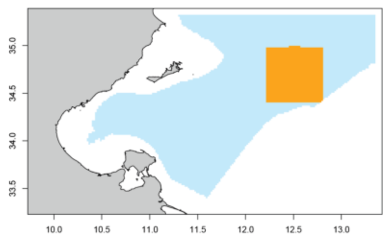
The Ecospace model of the Gulf of Gabes covers approximately 25,000 square cells, each covering 3.2 km^2. Nine habitat types were included. Each of the 41 functional groups was assigned to its preferred habitat, and each fishery fleet was assigned to the fishing zones authorized by Tunisian fisheries regulations. Ecospace was used mainly to assess scenarios of establishment of Marine Protected Areas (MPA). More details on Ecospace implementation and parameterization are available in Abdou et al. (2016).

3.3.2.4. Simulations of fishing management scenarios

Ecospace was used to simulate scenarios over a 15-year period (1995–2010). The baseline scenario reflects the state of the Gulf of Gabes ecosystem after 15 years under the current situation, which has no MPA and a 3-month biological rest period of demersal trawlers. In addition to the baseline scenario, seven fishing management scenarios were simulated. Most scenarios were assessed previously (Abdou et al., 2016; Halouani et al., 2016). Scenarios consisted of implementing temporal and spatial measures to explore potential ecosystem response (Table 3.2):

- Coastal MPA: establishment of a coastal MPA of 1900 km^2 in the southern part of the Gulf of Gabes
- Small offshore MPA: establishment of a small offshore MPA of 1300 km^2
- Large offshore MPA: establishment of a large offshore MPA of 3900 km^2
- 4-month rest period: increasing the demersal trawler rest period to 4 months
- 6-month rest period: increasing the demersal trawler rest period to 6 months
- 20% fewer demersal trawlers: eliminating the 20% of demersal trawlers with the worst overall environmental performance (according to LCA results regarding the intensity of environmental impacts)
- 50% fewer demersal trawlers: eliminating the 50% of demersal trawlers with the worst overall environmental performance (according to LCA)

Table 3.2 : Demersal trawling management plans in the Gulf of Gabes simulated with the Ecospace model. MPA = marine protected area. Orange represents the MPA, blue is the area included in the model and gray represents land.

Spatial managment scenarios		
 Coastal MPA	 Small offshore MPA	 Large offshore MPA
Temporal managment scenarios		
4-month rest period	6-month rest period	
Scenarios of decreasing the number of demersal trawlers		
20% fewer demersal trawlers	50% fewer demersal trawlers	

When using Ecospace to simulate the spatial management scenarios, the model redistributes the fishing effort according to the new regulations instead of reducing it. For each simulation, the model predicts changes in functional group biomass and the changes in yield (per group and per fishery). The new catch and biomass values (after a 15-year run) were used to recalculate the environmental performance (using LCA) and ecosystem indicators. All results were then compared to the baseline scenario. The EwE model was run separately and the results were used to supplement the results of the LCA for demersal trawlers to place this activity in an ecosystem context.

3.3.3. Results

3.3.3.1. LCA results for the current situation

Estimated environmental impacts of an average demersal trawler under the current situation are presented in (Table 3.3). Fuel and lubricating oil production is responsible for more than 96% of abiotic depletion potential (total = 93.9 kg Sb eq t^{-1}) and ozone depletion potential (total = 0.003 kg CFC-11 eq t^{-1}). It is also responsible for around 55% of photochemical oxidant formation (total = 2.4 kg C_2H_4 eq t^{-1}), marine ecotoxicity (total = 1,583,942 kg 1,4-DCB eq t^{-1}), land occupation potential (total = 119.2 m^2 year t^{-1}), and total cumulative energy demand (total = 212,637 MJ eq t^{-1}). Fish production is the largest contributor to acidification (84% of 155.8 kg SO_2 eq t^{-1}), global warming (81% of 13,773 kg CO_2 eq t^{-1}), and eutrophication (57% of 9.32 kg PO_4 eq t^{-1}). Paint and antifouling production contributes less than the other processes and is responsible for about 13% of marine ecotoxicity, land occupation, and total energy demand. Construction of the trawler and trawling net is responsible for 84% of terrestrial ecotoxicity (total = 88.8 kg 1,4-DCB eq t^{-1}) and human toxicity (57% of 4.094 kg 1,4-DCB eq t^{-1}), and also contributes to marine toxicity, land occupation, and total energy demand (30%). Transport does not contribute greatly to impacts (Table 3.3).

Table 3.3 : Contribution of operational stages to mean environmental impacts per t of seafood produced by an average demersal trawler in the Gulf of Gabes. ADP= Abiotic Depletion Potential; AP= Acidification Potential; EP= Eutrophication Potential; GWP= Global Warming Potential; ODP= Ozone Depletion Potential; POFP= Photochemical Oxidant Formation Potential; HTP= Human Toxicity Potential; METP= Marine Ecotoxicity Potential; TETP= Terrestrial Ecotoxicity Potential; LOP= Land Occupation Potential; TCED= Total Cumulative Energy Demand.

	Fish production	Fuel and lubricating oil production	Paint and antifouling production	Trawler and net construction	Transport	Total
ADP	0.000	90.261	0.553	3.052	0.037	93.902
%	0.000	96.122	0.588	3.250	0.039	100.000
AP	130.461	21.973	0.942	2.398	0.038	155.813
%	83.729	14.103	0.605	1.539	0.024	100.000
EP	5.328	3.078	0.468	0.443	0.003	9.320
%	57.167	33.031	5.016	4.753	0.032	100.000
GWP	11156.951	2,116.437	61.390	433.472	5.085	13,773.335
%	81.004	15.366	0.446	3.147	0.037	100.000
ODP	0.000	0.002	0.000	0.000	0.000	0.003
%	0.000	97.271	0.567	2.125	0.037	100.000
POFP	0.869	1.290	0.059	0.138	0.001	2.358
%	36.855	54.725	2.521	5.844	0.056	100.000
HTP	303.534	1,188.288	283.388	2,316.532	3.028	4,094.769
%	7.413	29.020	6.921	56.573	0.074	100.000
METP	0.001	889,555.051	215,540.865	477,733.424	1113.128	1,583,942.500
%	0.000	56.161	13.608	30.161	0.070	100.000
TETP	0.000	12.808	1.329	74.658	0.019	88.814
%	0.000	14.421	1.496	84.061	0.022	100.000
LOP	0.000	67.790	14.822	36.285	0.309	119.206
%	0.000	56.868	12.434	30.439	0.260	100.000
TCED	0.000	204,578.759	1,355.029	6,619.678	83.679	212,637.140
%	0.000	56.868	12.434	30.439	0.260	100.000

3.3.3.2. EwE indicators of the current situation

The pressure indicators reveal a PPR of yield of 240.6 kg of wet weight.t^{-1}.km^{-2} (126.9 and 113.8 kg of wet weight.t^{-1}.km^{-2} from primary producers and detritus, respectively). PPR/catch is 139.7 kg of wet weight.t^{-1}.km^{-2}. PPR and PPR/catch of demersal trawlers are 313.5 and 522.9 kg of wet weight.t^{-1}.km^{-2}, respectively. Total yield in the ecosystem is 1.72 t.km^{-2}.$year^{-1}$, and demersal trawler yield is 0.85 t.km^{-2}.$year^{-1}$. The exploited resources indicators reveal MTI of 3.85 and mean TLc of 3.44. The trophic chain indicators reveal mean trophic TE of 20.3% and API of 44%. Based on the keystone analysis, sharks are the most important trophic compartment in the Gulf of Gabes model, with a total biomass of 0.19 $t.km^{-2}$ (Table 3.4).

Table 3.4 : Mean Ecospace indicator results and environmental impacts per t of seafood produced by an average wooden demersal trawler in the Gulf of Gabes under the baseline scenario. The current situation represents the start of the simulation; the baseline scenario reflects results after 15 years in the same situation and with no management plan.

Characteristic or impact	Unit	Current situation	Baseline scenario	Percent change
Total yield	$t.km^{-2}.year^{-1}$	1.7	1.0	-10.8%
Demersal trawler yield	$t.km^{-2}.year^{-1}$	0.85	0.3	-37.2%
Total biomass	$t.km^{-2}$	78.7	65.6	-16.6%
Abiotic depletion potential	kg Sb	93.9	149.5	+59.2%
Acidification potential	kg PO_4	155.8	248.1	+59.2%
Eutrophication potential	kg SO_2	9.3	14.8	+59.2%
Global warming potential	kg CO_2	13773.3	21930.8	+59.2%
Ozone depletion potential	kg CFC-11	0.002	0.004	+59.2%
Photochemical oxidant formation potential	kg C_2H_4	2.3	3.7	+59.2%
Human toxicity potential	kg 1,4-DCB	4,094.7	6,519.9	+59.2%
Marine ecotoxicity potential	kg 1,4-DCB	1,583,943	2,522,056	+59.2%
Terrestrial ecotoxicity potential	kg 1,4-DCB	88.8	141.4	+59.2%
Land occupation potential	m^2year	119.2	189.8	+59.2%
Total cumulative energy demand	MJ	212637.1	338574.7	+59.2%
Primary production required (PPR)	kg of wet weight.$t^{-1}.km^{-2}$	240.6	314.6	+30.7%
PPR /catch	kg of wet weight.$t^{-1}.km^{-2}$	139.7	279.9	+100.4%
PPR of demersal trawlers	kg of wet weight.$t^{-1}.km^{-2}$	313.4	177.0	-43.5%
PPR /catch of demersal trawlers	kg of wet weight.$t^{-1}.km^{-2}$	522.9	518.7	-0.8%
Mean trophic index	-	3.8	3.8	+0.3%
trophic level of the catches	-	3.4	3.7	+10.4%
Apex predator indicator	%	44.0	49.5	+12.6%
Keystone group biomass (sharks)	$t.km^{-2}$	0.2	0.1	-52.3%

3.3.3.3. Scenario results

3.3.3.3.1. Baseline scenario

In the 15-year simulation of the current situation, Ecospace predicts that total yield decreases by 11% and demersal trawler yield decreases by 37%. Total biomass of functional groups decreases by 16%. LCA impacts after the 15-year simulation (calculated using the final catch values) show a 59% increase in all impacts. PPR increases by 31% to 314.61 kg of wet weight.t^{-1}.km^{-2}, while PPR/catch increases by 100% to 280 kg of wet weight.t^{-1}.km^{-2}. PPR of demersal trawlers decreases by 44%; however, PPR/catch of demersal trawlers decreases to 177 kg of wet weight.t^{-1}.km^{-2}. Total yield decreases by 20%, and demersal trawler yield decreases by 60%. MTI does not change (3.87). Although TL_C increases by 10%, API increases by 12% (reaching 50%). Biomass of the keystone group (sharks) in the Gulf of Gabes ecosystem decreases by 52% (Table 3.4).

3.3.3.3.2. MPA scenarios

Simulated scenarios of coastal MPA establishment have lower environmental impacts than the baseline scenario. All impacts increase by 22%, compared to 59% in the baseline scenario (Figure 3.8). Total PPR increases to 305.64 kg of wet weight.t^{-1}.km^{-2}, which is a 27% increase compared to 31% in the baseline scenario; however, PPR of demersal trawlers decreases as much as in the baseline scenario (44%). Total PPR/catch increases by 102%, compared to a 100% increase in the baseline scenario. PPR/catch of demersal trawlers decreases by 1.6% compared to 0.8% in the baseline scenario. Total yield decreases by 37%, and demersal trawler yield decreases by 60%. MTI remains the same. TL_C increases by 6% to 3.6 compared to 3.8, and the API increases to reach 50% instead of 44%. The keystone group biomass decreases to 0.08 t.km^{-2} (Figure 3.9).

Simulated scenarios of offshore MPA establishment have lower environmental impacts than the baseline scenario. All impacts increase by 27% with a small offshore MPA and 26% with a large offshore MPA, compared to 59% in the baseline scenario (Figure 3.8). Total PPR, PPR/catch, PPR of demersal trawlers and PPR/catch of demersal trawlers experience similar changes as the baseline scenario for both MPAs. Total yield decreases by 34% and demersal trawler yield decreases by 60% for both MPAs. MTI does not change. TL_C increases to 3.8, and API increases to 50% (same as the baseline scenario). Keystone group biomass decreases by 52%, to 0.09 t.km^{-2} for both MPAs (Figure 3.9).

3.3.3.3.3. Rest period scenarios

According to the 15-year simulations, establishment of 4-month and 6-month rest periods decrease all environmental impacts by 7% and 15%, respectively (Figure 3.8), which is better than the 59% increase in impacts in the baseline scenario. In both cases, total PPR increases by 38%, PPR/catch increases to 85%, and PPR/catch of demersal trawlers decreases by 6%; however, PPR of demersal trawlers decreases by 21% and 15% with 4-month and 6-month rest periods, respectively. Total yield decreases by 25% (1.3 t.km^{-2}.year^{-1}), and demersal trawler yield decreases by 40% and 37% with 4-month and 6-month rest periods, respectively. MTI remains the same. TL_C increases to 4.3, and API increases to reach 50%. The keystone group biomass decreases by 55% (0.08 t.km^{-2}) for both rest periods (Figure 3.9).

3.3.3.3.4. Scenarios for decreasing the number of demersal trawlers

Effects of decreasing the number of demersal trawlers vary by impact category. According to the 15-year simulations, abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion, photochemical oxidant formation and total cumulative energy demand increase by approximately 33% and 4% when 20% or 50% of demersal trawlers were eliminated, respectively. Marine aquatic ecotoxicity and land occupation increase by 14% and 6%, respectively. Human toxicity increases by 3% when 20% of demersal trawlers were eliminated and decreases by 14% when 50% of demersal trawlers were eliminated. Terrestrial ecotoxicity decreases by 7% and 23% when 20% or 50% of demersal trawlers were eliminated, respectively (Figure 3.8). When 20% of demersal trawlers were eliminated, total PPR increases by 30% and PPR/catch increases by 92%. PPR and PPR/catch of demersal trawlers decreases by 70% and 3%, respectively. Total yield decreases by 33% and demersal trawler yield decreases by 79% when 20% of demersal trawlers were eliminated; however, when 50% of the trawlers were eliminated, total yield decreases by 35% and demersal trawler yield decreases by 84%. MTI remains the same. TL_C increases by 16% when 20% of trawlers were eliminated and increases by 10% when 50% of trawlers were eliminated. API increases by 1.5% in both scenarios. Keystone group biomass decreases by 50%, to 0.09 t.km^{-2} in both scenarios (Figure 3.9).

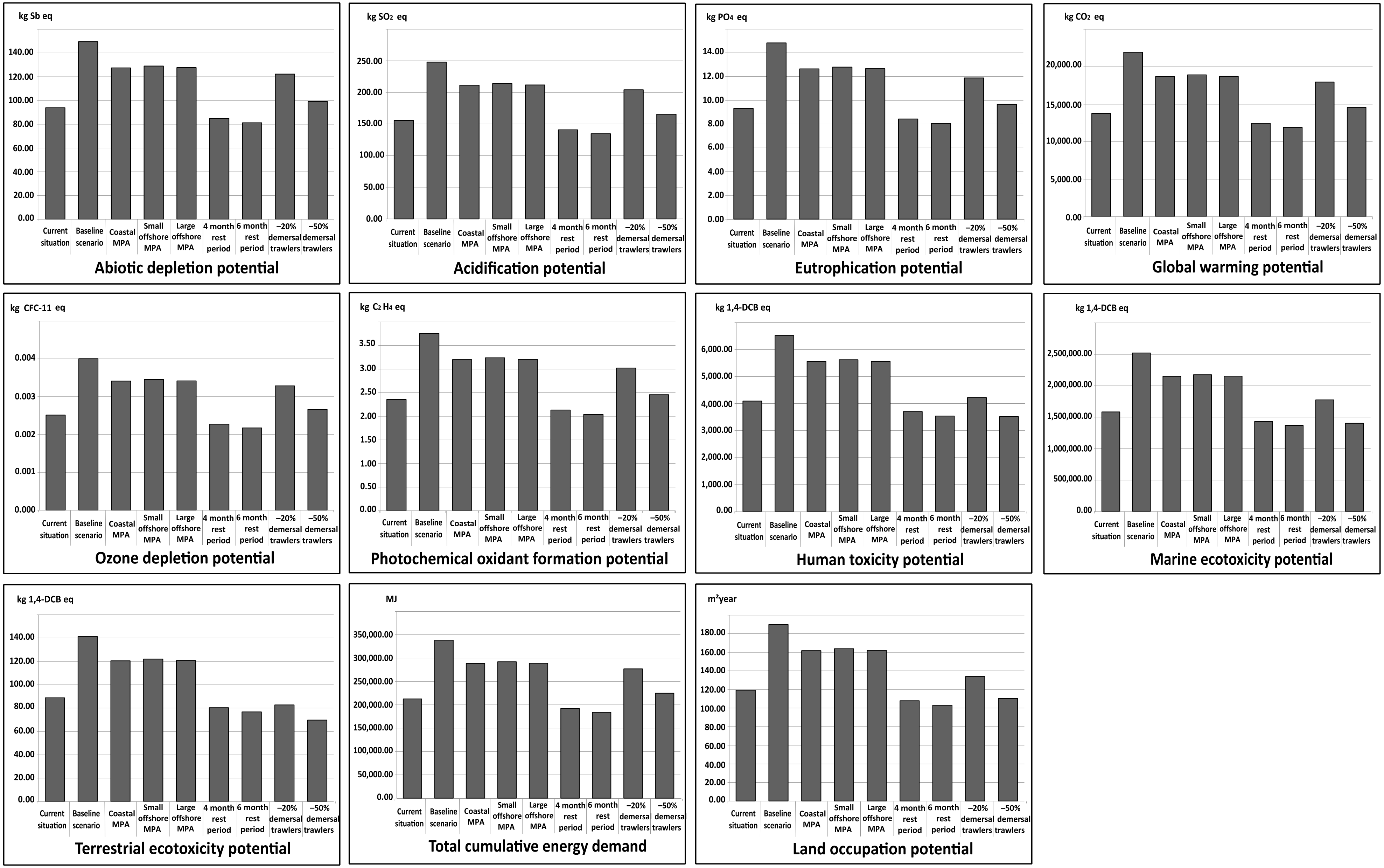


Figure 3.8 : Environmental impacts per t of seafood produced by an average demersal trawler in the Gulf of Gabes in the current situation and under eight 15-year scenarios.

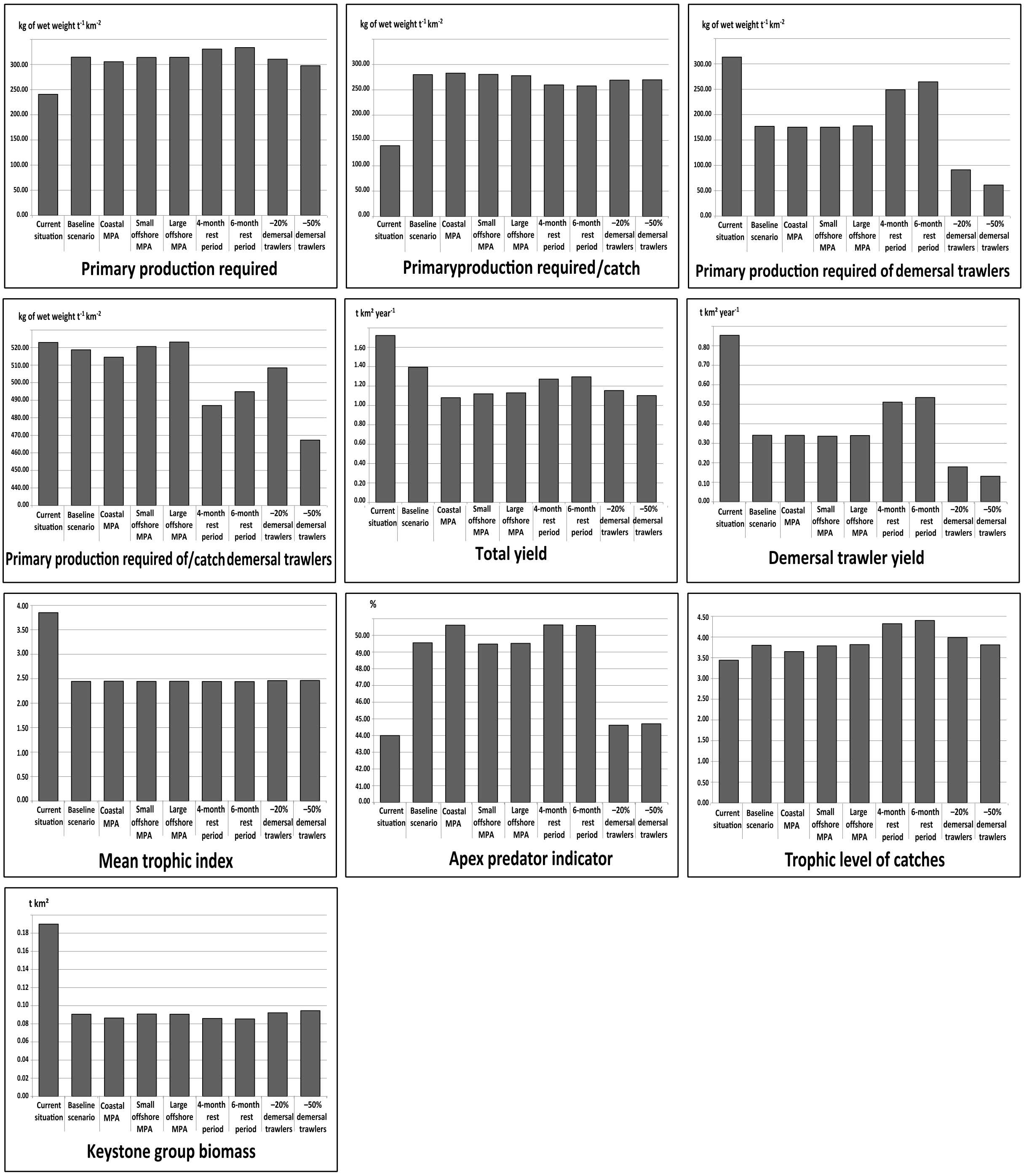


Figure 3.9 : Ecospace indicator results in the Gulf of Gabes under the current situation and eight 15-year scenarios

3.3.4. Discussion

LCA impacts calculated for 1 t of landed seafood showed that fuel and lubricating oil production and fish production contribute most to environmental impacts. This large contribution is due to the use of demersal trawling, which has the most fuel-intensive gear

(Avadí and Fréon, 2013b; Schau et al., 2009). Avadí and Fréon, (2013) stated that fuel production contributes most to environmental impacts of fishing vessels, and several fishery LCAs demonstrated that fish production is a major contributor to many impact categories (Ziegler et al., 2003; Hospido and Tyedmers, 2005; Pelletier et al., 2007; Schau et al., 2009; Vázquez-Rowe et al., 2012b). Paint and antifouling production contributed the most to marine ecotoxicity, and also to land occupation and total cumulative energy demand due to emissions of copper, xylene, lead, tributyltin and zinc oxides. In many fishery-related LCAs, trawler and fishing gear construction were not considered due to its supposedly small contribution to environmental impacts (Avadí and Fréon, 2013b). However, other studies found large impacts of the construction phase (Fréon et al., 2014; Svanes et al., 2011). In this study, construction contributed more than 80% of terrestrial ecotoxicity, more than 50% of human toxicity, and more than 30% of marine toxicity, land occupation and total cumulative energy demand. Thus, it seems necessary to include the construction phase in fishery LCA studies due to its large contribution to environmental impacts, especially toxicity impacts. Transport contributes much less to impacts than to the other processes, which suggests that it is not key subsystem of demersal trawling in the Gulf of Gabes.

Although LCA provides complete environmental assessment from "cradle-to-grave", several key impacts are still lacking. To ensure the sustainability of fishing, it is important to consider ecosystem state. EwE provides ecosystem indicators to describe ecosystem state and impacts of fisheries on the ecosystem. PPR, one of the most common pressure indicators to describe ecosystem state, is widely used in LCA studies because it provides a measure of biotic resource use. Although PPR is commonly applied to seafood products, its fundamental assumptions can be challenged. For example, PPR is calculated by assuming a TE of 10% per trophic level. However, Libralato et al. (2008) estimated variability in TE ranging from 5-14% depending on the type of ecosystem and fish species variability. Luong et al. (2015) showed that standard estimates of PPR are 3.9-5.0 times as high as those estimated when adopting the food-chain theory. We chose to calculate PPR using EwE, which considers the entire ecosystem and interactions between its compartments and fisheries.

Official statistics and stock assessments indicate that the Gulf of Gabes is a highly fished area. Most targeted species are over-exploited or fully exploited (e.g. *Pomatomus saltatrix* (Dhieb et al., 2007), *M. surmuletus* (Ben Meriem et al., 1994b), *M. barbatus* (Gharbi et al., 2004), *Pagellus erythrinus* (Jarboui et al., 1998)). Indicators from EwE indicate that fishing is unsustainable in the Gulf of Gabes. LCA results demonstrated that demersal trawling in the gulf has high environmental impacts in all categories. Consequently, it is necessary to establish fishery management measures, such as MPAs, rest periods, and a substantial reduction in fishing effort.

We used the Ecospace module as a decision support tool to assess fishery management scenarios in the context of Ecosystem-Based Fishery Management. Impacts in all categories increased by 59% after a 15-year run of the baseline scenario (no management plan). All management measures had a positive impact on the environmental performance and decreased all impacts compared to the baseline scenario. MPA scenario results were better when a small coastal MPA or a large offshore MPA was established, due to the type of habitat it covered. Previous studies demonstrated the importance of bottom characteristics in establishing a successful MPA (Guizien et al., 2012). The rest-period scenarios provided the best results for environmental impacts and ecosystem indicators (except for PPR and PPR of demersal trawlers) among all the scenarios assessed. Extending the rest period decreased all impacts compared to those of the baseline scenario (Table 3.5). Impacts of demersal trawlers decreased as the duration of the rest period increased: 4-month and 6-month rest periods decreased impacts by 7% and 15%, respectively, compared to those in the baseline scenario. Decreasing the number of demersal trawlers by 20% or 50% had better results for terrestrial, marine and human toxicity than the MPA scenarios. For the other impact categories, the 20% decrease provided the worst results among all scenarios (33% increase), and the 50% decrease provided better results than the MPA scenarios. Total PPR and PPR/catch did not differ greatly among scenarios and, as expected, PPR of demersal trawlers was higher than that of the baseline when the rest period was extended and was lower than that of the baseline when the number of trawlers decreased. For the seven simulated management scenarios, total yield decreased compared to that of the baseline scenario; however, demersal trawler yield increased when the rest period was extended and decreased when the number of trawlers decreased. Simulation results indicate that the management measures increased TLc, except for the establishment of MPAs. API increased with the coastal MPA and the extent of the rest period, and decreased when the number of demersal trawlers decreased. The management scenarios were intended only to help understand ecosystem functioning and are not for direct application. The scenario results would interest stakeholders because they could help to identify management scenarios that would maintain or increase landings while also providing adequate environmental performance and not compromising ecosystem structure.

The overall results indicate that EwE indicators are able to supplement LCA results to provide a complete assessment of fisheries and place them in an ecosystem-based management context. However, this study could improve on many levels. The LCA results would be more accurate if the boundaries were extended to include post-harvesting processes related to demersal trawler yield. In addition, conducting LCA to include all fisheries in the EwE model may provide better insight into the fishing activity and state of the Gulf of Gabes ecosystem. Thus, it may help in developing effective management plans to ensure sustainability. The EwE model would also improve if more updated ecosystem data were available, especially due to the high uncertainty of parameters in Ecopath. The uncertainty in Ecospace and LCA should be considered when interpreting the results. We focused on trends when comparing the management scenarios to reduce the uncertainties related to data reliability and the complexity of the ecosystem.

Table 3.5 : Changes in impact categories and ecosystem indicators compared to the baseline scenario under seven management scenarios simulated using Ecospace. MPA: marine protected area.

Total catch	Baseline scenario	Coastal MPA	Small offshore MPA	Large offshore MPA	4-month rest period	6-month rest period	-20% demersal trawlers	-50% demersal trawlers
Abiotic depletion potential	−−−	−−	−−	−−	+	+	−−	−
Acidification potential	−−−	−−	−−	−−	+	+	−−	=
Eutrophication potential	−−−	−−	−−	−−	+	+	−−	=
Global warming potential	−−−	−−	−−	−−	+	+	−−	−
Ozone depletion potential	−−−	−−	−−	−−	+	+	−−	−
Photochemical oxidant formation	−−−	−−	−−	−−	+	+	−−	−
Human toxicity potential	−−−	−−	−−	−−	+	+	=	+
Marine ecotoxicity potential	−−−	−−	−−	−−	+	+	=	+
Terrestrial ecotoxicity potential	−−−	−−	−−	−−	+	+	+	++
Land occupation potential	−−−	−−	−−	−−	+	+	−	=
Total cumulative energy demand	−−−	−−	−−	−−	+	+	−−	+
Primary production required (PPR)	−−	−−	−−	−−	−−−	−−−	−−	−−
PPR/catch	−−−	−−−	−−−	−−−	−−	−−	−−−	−−−
PPR demersal trawlers	++	++	++	++	+	+	+++	+++
PPR/catch demersal trawlers	=	+	=	=	+++	+++	++	+++
Total yield	−−	−−−	−−−	−−−	−−	−−	−−−	−−−
Demersal trawler yield	−−	−−	−−	−−	−	−	−−−	−−−
Marine trophici ndex	=	=	=	=	=	=	=	=
Trophic level of catches	++	+++	++	++	+++	+++	=	=
Apex predator indicator	=	=	=	=	+	+	=	=
Keystone group biomass	−−−	−−−	−−−	−−−	−−−	−−−	−−−	−−−

= Impact intensity / indicator value are the same as the current situation

− , + Slightly worse or better impact / indicator compared to the current situation

−− , ++ Moderately worse or better impact intensity / indicator compared to the current situation

−−− , +++ Much worse or better impact / indicator compared to the current situation

3.3.5. Conclusion

This study developed a framework to supplement the LCA of seafood production with ecosystem indicators from EWE. The Gulf of Gabes was used as a case study to conduct the LCA, which was combined with the EwE model to provide a complete assessment of the environmental performance and ecosystem characteristics associated with production of seafood landed by demersal trawlers. LCA results showed that fish production, fuel and lubricating oil production, and paint and antifouling production were the main contributors to environmental impacts. Thus, to improve the overall environmental performance, Ecosystem indicators from the EwE model provide valuable information to conduct environmental analysis using LCA and place it in the context of an ecosystem approach to fisheries. The Ecospace module of EwE was used to simulate management scenarios. All management scenarios decreased environmental impacts compared to those of the baseline scenario; however, ecosystem indicators varied more among scenarios. Among the scenarios, extending the rest period to 6 months is the most effective management plan, which increases total yield and demersal trawler yield compared to those of the baseline scenario. Total PPR of demersal trawlers increased in this scenario, but PPR/catch of demersal trawlers greatly decreased. API and TLc increased with the implementation of this measure. Results of this study provide stakeholders and policy makers with practical information that can help identify the most effective management plan, since ecosystems may respond differently to management measures depending on their characteristics.

3.4. Conclusion et perspectives du chapitre

Dans ce chapitre nous avons appliqué l'ACV à la pêche au chalut de fond dans le Golfe de Gabès. Il s'agit de la première tentative d'utilisation de l'ACV pour évaluer les impacts environnementaux de l'activité de chalutage dans le Sud de la Méditerranée. La classification des chalutiers de fonds selon l'intensité des impacts environnementaux qu'ils génèrent, a révélé un contraste important entre les différents groupes de chalutiers.

Les résultats de cette analyse ont montré que les impacts sont proportionnels à la quantité de carburant nécessaire pour la production d'une tonne de produit de la mer. En effet, les chalutiers qui pêchent le moins ont un impact environnemental par tonne de produits de la mer plus élevé, due à la faible efficacité d'utilisation du carburant et la faible quantité de capture par unité d'effort. Ceci caractérise généralement les navires qui ciblent les espèces à forte valeur commerciale (comme la crevette). Les résultats de l'ACV ont également montré que les activités à bord des chalutiers (phase de production de poissons), ainsi que la production du carburant et de l'huile lubrifiante sont les processus qui contribuent le plus aux impacts environnementaux. En se basant sur ces résultats, nous pouvons conclure qu'il faut améliorer l'efficacité d'utilisation du carburant pour améliorer le bilan environnemental des chalutiers de fond dans le Golfe de Gabès. Il faut donc diminuer la consommation du carburant par tonne de produit de la mer. Pour cela, il faudrait améliorer les pratiques de pêche en utilisant par exemple des moyens électroniques pour la sélection des zones de pêche et des systèmes électroniques d'injection de carburant. De plus, le changement de la forme de la coque des chalutiers et le type de moteur peut augmenter l'efficacité d'utilisation du carburant. Le remplacement du carburant fossile par du biocarburant permet également d'améliorer le bilan environnemental de la pêche.

L'ACV est un outil pertinent pour l'évaluation environnementale, par contre cette méthodologie ne prend pas en compte la composante écologique de l'écosystème. Pour remédier à ce manque, un modèle trophique (EwE) (développé et publié auparavant par Hattab et al. (2013) a été utilisé. EwE permet de calculer plusieurs indicateurs de fonctionnement de l'écosystème, qui ont servi à compléter l'analyse environnementale par une analyse écosystémique. Ces indicateurs sont utiles pour décrire l'état de l'écosystème et ses interactions avec l'activité de pêche, ce qui permet de placer le chalutage de fond dans le cadre de l'approche écosystémique de pêche. Le module spatialisé Ecospace a permis d’évaluer les conséquences environnementales et écosystémiques de différentes mesures de gestion (implémentation d’aires marines protégées, prolongation de période de repos biologique, diminution du nombre de chalutiers de fond) simulées dans le Golfe de Gabès. En se basant sur les résultats des simulations, nous pouvons conclure que la prolongation de la période de repos biologique est la mesure de gestion la plus efficace parmi les scénarios testés d'un point de vue environnemental. En effet, l'extension de trois à six mois de la période du repos biologique a engendré une augmentation des impacts environnementaux étudiés de 15% au lieu d'une augmentation de 59% dans le cas de seulement 3 mois de repos biologique. Cette mesure de gestion peut également aboutir à l'augmentation des captures totales et des captures des chalutiers de fond dans le Golfe de Gabès. Cette analyse peut être utilisée par les autorités et les décideurs pour déterminer les mesures de gestion les plus adaptés et efficaces dans le Golfe de Gabès, sur le plan environnemental et écosystémique.

Les analyses conduites dans ce chapitre peuvent être améliorées en étendant les frontières du système étudié dans l'ACV, d'une manière à inclure les opérations et les processus post-débarquements des produits de la mer. Il pourrait également être intéressant de prendre en compte la dimension spatiale et temporelle dans l'analyse environnementale, vu la variabilité importante des impacts environnementaux des navires d'une année à l'autre et d'une zone de pêche à l'autre. Étudier les impacts environnementaux d'autres pêcheries peut apporter des informations utiles aux décideurs quant aux types de pêcheries et engins qu'il faut encourager pour assurer la durabilité du secteur de la pêche. Le modèle EwE pourrait être amélioré par l'inclusion de plus de données afin de réduire l'incertitude des paramètres inclus dans le modèle. Avec l'expansion rapide de l'activité aquacole, il est intéressant de comparer la pêche et l'aquaculture sur le plan socio-économique et environnemental. Dans ce chapitre, les ACV ont montré leur capacité à conduire une évaluation environnementale utile pour comprendre les conséquences de la pêche sur l'environnement. Mais pour une analyse plus complète et précise du secteur de la pêche, il est nécessaire de prendre la composante écosystémique en considération. Pour cela les indicateurs écologiques obtenus du modèle EwE sont appropriés pour compléter les résultats de l'ACV.

Chapitre 4

Comparaison des impacts environnementaux de l'aquaculture et du chalutage de fond en Tunisie : analyse de cycle de vie et méta-analyse

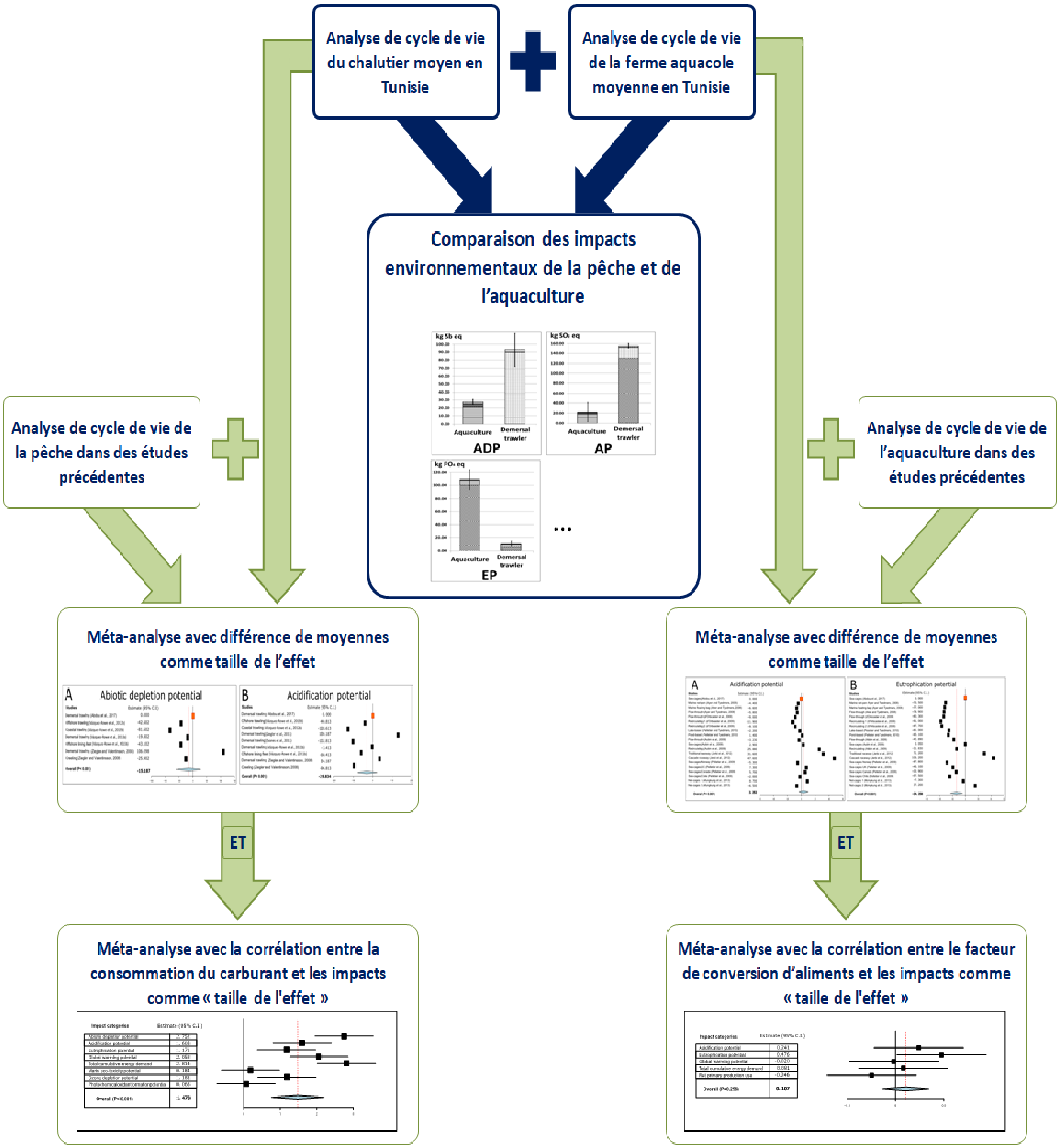
4.1. Introduction du chapitre

Ce chapitre s'appuie sur un article scientifique soumis dans le journal "Journal of Cleaner Production" (manuscrit E, Abdou et al. in prep, section 4.2 du présent chapitre). Dans ce chapitre, les impacts environnementaux de la pêche au chalutage de fond et de l'élevage du bar et de la daurade dans des cages en mer en Tunisie ont été comparés. Le bilan environnemental de la production d'une tonne de capture par un chalutier de fond moyen a été comparé à celui de la production d'une tonne de poissons par une ferme aquacole moyenne en Tunisie. Le cadre méthodologique de l'ACV a été utilisé pour le calcul des impacts environnementaux des deux activités. Les catégories d'impacts comparées sont : l'épuisement des ressources abiotiques, l'acidification, l'eutrophisation, le réchauffement climatique, l'appauvrissement de la couche d'ozone, la formation d'oxydants photochimiques, la toxicité humaine, l'écotoxicité marine, l'écotoxicité terrestre, l'occupation des surfaces terrestre et la demande d'énergie cumulée. De plus, nous avons estimé l'impact de la pêche et de l'aquaculture sur les fonds marins. L'ACV a permis d'étudier les impacts environnementaux de la production des produits de la mer en prenant touts les processus qui interviennent en considération. En revanche, la fin de vie du produit et les étapes post-production et post-débarquement (stockage, emballage, traitement, distribution, etc) ne sont pas prises en compte dans cette étude.

Ensuite, une méta-analyse a été conduite pour comparer les impacts environnementaux du chalutage de fond et de l'aquaculture en Tunisie à ceux d'autres méthodes et systèmes de production de produits de la mer. La méta-analyse est une analyse statistique qui permet de combiner les résultats d'une série d'études indépendantes sur un même problème et répondant à une même question scientifique. Cette méthode se base sur le calcul de la

« taille de l'effet » ou « grandeur de l'effet » (« effect size » en anglais). La taille de l'effet est une mesure de l'intensité de la relation entre les variables d'intérêts. Elle est calculée par plusieurs méthodes selon le domaine de recherche et les données à comparer. Les méthodes de calcul de la taille de l'effet les plus utilisées sont : le calcul de la différence standardisée entre les moyennes, le calcul du coefficient de corrélation de Pearson, le rapport de cote (odds ratio) qui compare la probabilité d'un événement dans deux groupes. La méta-analyse a été développée en prenant la différence des moyennes entre impacts de pêche et de l'aquaculture rapportée dans des études d'ACV comme « taille de l'effet ». Ensuite, la méta-analyse a été reconduite en utilisant la corrélation entre la consommation du carburant et les impacts environnementaux dans les études ACV pêche, et entre le facteur de conversion d'aliments et les impacts environnementaux dans les études ACV aquaculture.

Résumé graphique de la méthodologie utilisée dans le manuscrit E



4.2. Manuscrit E "Comparing environmental impacts of aquaculture and demersal trawling activity using life cycle assessment (LCA) framework and meta-analysis"

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Abstract

Fisheries and aquaculture play an important role in socio-economy and food security in Tunisia. In Tunisia, demersal trawling is the main fishing activity and seabass and seabream rearing in sea-cages in the predominant aquacultural activity. Life Cycle Assessment (LCA) was applied to compare both sectors. We compared the environmental impact associated with the production of 1 t of seafood landed by demersal trawling and 1 t of seabass and seabream produced on sea-cage aquaculture farms. Impact categories compared in the study were abiotic depletion potential, acidification potential, eutrophication potential, global warming potential, ozone depletion potential, photochemical oxidant formation potential, human toxicity potential, marine eco-toxicity potential, terrestrial eco-toxicity potential, land occupation potential, and total cumulative energy demand. In addition, seafloor damage related to both activities was estimated. A meta-analysis was carried out to compare Tunisian case with other worldwide fisheries and aquaculture activity. Results revealed that aquaculture had only higher eutrophication and land occupation potential than demersal trawling. Most impacts of demersal trawling were related to onboard activity and to the production of fuel and lubricating oil. Therefore, improvements must focus on minimizing fuel consumption. Fish feed emerged as the main contributor to most impacts associated with aquaculture activity; this is directly related to the high food conversion ratio (FCR) and to the use of fish meal and fish oil as principal ingredients. Improvements should focus on the optimization of production and use of fish feed and to follow better feeding strategies and farming practices aiming at decreasing the FCR. LCA is a valuable tool for assessing how to improve environmental sustainability of demersal trawling and aquaculture; it provides stakeholders with insights into the main operational issues that require improvement.

Keywords: Life Cycle Assessment, Marine aquaculture, Demersal trawling, Environmental impact, Tunisia.

4.2.1. Introduction

Seafood production represents an important source of nutrition and income for hundreds of people around the world. The world seafood consumption has increased from 9.9 kg per capita in the 1960s to 19.7 kg in 2013, with preliminary estimates exceeding 20 kg per capita for 2014 and 2015 (FAO, 2016). This explains the substantial expansion of seafood production and trade over the past five decades (Halpern et al., 2008). In 2014, seafood products represent more than 9% of the economic value of total agricultural exports. The growth in fish consumption resulted in the improvement of human diets; indeed, fish accounted for 17% of the global population's intake of animal protein and 6.7% of all protein consumed. In addition, it provides 20% of the average per capita intake of animal protein for 3.1 billion people. However, the growth in demand is no longer sustained by fisheries, which has remained stable for more than 10 years. The global production from marine fisheries increased to reach 86 million tons in 1996 and then stagnated, and even slightly decreased to reach 81.5 million ton in 2014 due to the overexploitation of several fish stocks (FAO, 2016). The Food and Agriculture Organization estimated that only 25% of world's fisheries are sustainably exploited and half are fully exploited (FAO, 2016). With the stagnation of fisheries production, aquaculture exhibited a consistent and vigorous growth in the supply of fish for human consumption. Aquaculture provided 7% of fish in 1974 and this percentage increased to reach 39% in 2004. Aquaculture production kept on increasing with a rate of 23.5% from 2009 to 2014. In 2014, aquaculture production reached 73.8 million tons and it provided 44% of the total consumed fish and this share is expected to exceed 52% by 2025 (FAO, 2016).

Fishing is considered as the last food production activity that relies entirely on extracting organisms directly from ecosystems (Christensen et al., 2003). Aquaculture is the fastest growing animal food production sector in the world (FAO, 2016). Both activities entail risks of negative impacts on the environment and ecosystems (Kaiser and de Groot, 2000; Read and Fernandes, 2003). Due to the worrying state of world fishing stocks, environmental impacts of seafood production have been addressed in several scientific studies over the last year (World Bank, 2017; Worm et al., 2009); however, most environmental studies focus on the direct impacts and biological concerns of both activities. The evaluation of environmental impacts of fisheries concentrated principally on targeted species stocks (Costello et al., 2016), over-fishing (Ellingsen and Aanondsen, 2006), by-catch and discards (Glass, 2000), sea-bottom ecosystems and benthic communities alterations and disturbances (Guyonnet et al., 2008; Kaiser et al., 2006), and modifications in trophic structure and functioning of ecosystems (Tremblay-Boyer et al., 2011). Impact assessment of aquaculture focused on local effects in the surroundings of the fish farm by pollutants and wastes emissions (Read and Fernandes, 2003), dispersal of non-native species, release of antibiotics and pharmaceuticals into the water and disease transmission (Pelletier and Tyedmers, 2008), in addition to the potential negative influence on biodiversity (Tovar et al., 2000) and benthic communities (Karakassis, 2000). Those impact assessment studies overlook many important aspects related to the performance of fishing and fish-farming. For instance, only few fisheries studies included impacts of related to fuel consumption (Thrane, 2004; Tyedmers et al., 2005), paint and antifouling paint (Hospido and Tyedmers, 2005), energy and material use in the construction and maintenance of fishing vessels and fishing gear

(Hayman et al., 2000; Ziegler et al., 2003). Most traditional environmental studies of aquaculture ignore impacts related to industrial processes involved in fish farming, such as feed production, extraction of raw materials, construction and use of infrastructure and equipment (Farmaki et al., 2014; Luna et al., 2013; Ottinger et al., 2016; Sánchez-García et al., 2014).

The long-term sustainability of fishing and aquaculture industries is in jeopardy from ecological and environmental view-point. Because of the increasing impacts of both sectors, at local and global scales, it becomes important to implement a science-based approach to impact assessment that takes into consideration the whole supply chain and processes intervene in seafood production (Pelletier et al., 2007). From this perspective, Life Cycle Assessment (LCA) has proven to be a robust tool to better understand and estimate the potential environmental consequences of fisheries and aquaculture and ensure its long-term sustainability (Pelletier et al., 2007; Samuel-Fitwi et al., 2012). LCA is a standardised analytical tool (ISO, 2006a, 2006b) for estimating environmental impacts, "from cradle to grave", and identifying their sources (Guinée et al., 2002). It provides a complete view of connections between production systems and the environment. This methodological framework was applied to different fisheries (Abdou et al., 2018; Avadí et al., 2015; Fréon et al., 2014; Hospido and Tyedmers, 2005; Vázquez-Rowe et al., 2012a, 2012c, 2011b) and different aquaculture production systems (Abdou et al., 2017a, 2017b; Aubin et al., 2009; Ayer and Tyedmers, 2008; d'Orbcastel et al., 2009; Jerbi et al., 2012; Medeiros et al., 2017; Mungkung et al., 2013; Pelletier and Tyedmers, 2010).

Tunisia is located in northern Africa and occupies a central place in the Mediterranean Sea. It has more than 1300 km of coastline; fisheries and aquaculture play an important role in socio-economy and food security. Since 1990, the annual Tunisian per capita consumption of seafood increased by 32% and reached 9.5 kg per capita in 2014 (FAO, 2016). Based on the statistics of Tunisian Department of Fisheries and Aquaculture (Direction Générale de la Pêche et de l'Aquaculture (DGPA)), fisheries production increased from 110,900 in 2006 tons to 131,700 tons in 2015 (DGPA 2015). The main fishing ground in the country is the Gulf of Gabes, which is located on the southeastern coast. It has a shallow slope, soft bottom and high fish diversity, and it provides more than 40% of national seafood production. The Gulf of Gabes is also one of the of the most productive areas in the Mediterranean Sea in terms of catches (Papaconstantinou and Farrugio, 2000). The dominant fishing gear in this ecosystem is demersal trawling (Hattab et al., 2013; Mosbah et al., 2013), which is considered as one of the most destructive gear because it damages benthic habitats and communities and because of its non-selectivity (Kumar and Deepthi, 2006). Catches are dominated by Sparidae (*Diplodus annularis*), round sardinella and European pilchard (*Sardinella aurita*, *Sardina pilchardus*) and several benthic cephalopods (e.g. *Sepia officinalis*, *Octopus vulgaris*). The environmental performance of demersal trawling activity in the Gulf of Gabes was assessed using LCA in Abdou et al. (2018). Tunisian aquaculture activity is principally marine-oriented with an annual production of 14,230 tons in 2015 (DGPA 2015). In 2015, the number of offshore aquaculture farms reached 24 (only 7 fish farms in 2009). The main reared species are European seabass (*Dicentrarchus labrax*) and gilthead seabream (*Sparus aurata*), they had the highest economic values among agronomic products and a market prices of US$3.90-$5.20 and US$3.50-$4.30 per kilogram, respectively (FAO, 2016). Most of the fish produced in Tunisia is destined to local consumption. LCA was performed to assess environmental impacts of all sea cage aquaculture in Tunisia in Abdou et al. (2017a).

The objective of the present study is to compare the environmental performance of sea cage aquaculture farms with the demersal trawling activity in Tunisia using LCA methodology. In addition, a quantitative meta-analysis was performed in order to compare results in Tunisia with previous published studies. To our knowledge, this is the first attempt to compare seafood LCA studies through meta-analysis framework.

4.2.2. Material and Methods

4.2.2.1. Life Cycle Assessment (LCA)

LCA is a method to evaluate the potential environmental impacts associated with a product, process or a service taking into account its entire production life cycle from the extraction of raw materials through production, construction, use, waste management and disposal or recycling (Consoli et al., 1993; Guinée et al., 2002). It is a standardized method according to the an ISO-14040 (ISO (The International Organization for Standardization), 2006a, 2006b) that has emerged as a robust decision-support tool for policy makers. The International Reference Life Cycle Data System (European Commission, 2010) recommended four linked steps to perform LCA: (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment and (iv) interpretation.

- Goal and scope definition: it provides a detailed description of the system boundaries, which represents the delimitation of which processes to be included in the study. In this step, the functional unit should be decided. The functional unit is the reference to which impacts will be related; it should be clearly defined and measurable. The main goal of our study is to estimate and compare environmental impact of the average sea-cage aquaculture farm and the average demersal trawler in Tunisia. In addition to analyzing the contribution of production stages to environmental impacts in order to determine the main drivers of impacts. The functional unit for this study is "one ton of live fish" at the fish farm gate (for aquaculture) and one ton of landed seafood at the fishing port (for demersal trawling). No allocation was made between co-products (i.e. species) of both production systems and they were merged into a single product (“seafood”). Processes considered in the aquaculture assessment were fish production (farm activity), fish feed production and import, fingerlings and their importation, energy requirements, infrastructure, equipment and material transportation. The outputs included fish produced, nitrogen (N) and phosphorus (P) emitted in solid and dissolved forms. Maintenance phase was not considered for the aquaculture LCA. Demersal trawling system boundaries included fish production (onboard activities and emissions to water, air and soil), trawler and trawl net construction and maintenance, paint and antifouling paint production, fuel and lubricating oil production and transport. Trawler end-of-life phase was not included for demersal trawling LCA. For both seafood production systems, we excluded different post-farm stages (e.g. packaging and commercialization, use, disposal at the end of life). The system boundaries used for both LCAs were from "cradle-to-gate" (Guinée et al., 2002) (i.e farm gate or port gate).
- Life cycle inventory (LCI): this stage is straight-forward accounting of flows from and to nature involved in the product "system boundaries". Inventory includes raw resources and materials, energy, emissions to air, water and soil. All data are collected for all processes considered in the study and must be related to the

functional unit, previously defined. LCI of the average aquaculture farm and the average demersal trawler were compiled for one year of production and based on data obtained from official records of the DGPA. LCI aquaculture data encompasses a wide range of information on aquaculture farms (production characteristics, fish feed quantity and origin, number and origin of fingerlings, energy required, number and characteristics of cages, infrastructure and equipment (vessels and machines). Several interviews with managers and fish farms workers and field trips were conducted to validate and gather more detailed information. Data on fish feed chemical composition and ingredients were determined based on commercial labels and were supplemented with laboratory analysis. Nutrients emitted by the aquaculture farms, under solid or dissolved form of metabolic waste containing nitrogen and phosphorus, were estimated using a mass-balance model (Cho and Kaushik, 1990). This method was validated and used in several published aquaculture LCA (Bureau et al., 2003; Aubin et al., 2009; Mungkung et al., 2013; Abdou et al., 2017b). Further details about the LCI and its implementation could be found in Abdou et al. (2017a, 2017b). LCI data of demersal trawling contains information about length, tonnage, engine, engine power, lightship weight of each vessel. Several surveys with demersal trawler skippers and fishermen were conducted in the port of Sfax to obtain detailed data regarding operational aspects (e.g. fuel consumption, number of fishing trips, number of days at sea) and in the shipyard to gather data on the building of trawling vessels and trawl nets (e.g. material used for construction, paint and antifouling paint quantities, dimensions of vessels, life span). Fuel consumption data were estimated based on data on fuel quantities consumed per day and/or per fishing trip, fuel consumption as a function of engine power and brand, number of fishing trips and their durations, and engine power. Then emissions were estimated based on the EMEP/EEA air pollutant emission inventory guidebook (EMEP/EEA, 2016). Composition of paint and antifouling was determined from material safety data sheets. Then emissions were estimated based on the assumption that two-thirds of the paint and antifouling paint applied is released into the water (Hospido and Tyedmers, 2005). Maintenance phase was taken into account by adding 25% of the total amount of wood used for construction (Tyedmers, 2000). Detailed LCI of demersal trawling could be found in (Abdou et al., 2018). Required background data for both activities were obtained from the ecoinvent v3.0 database (Weidema et al., 2013).

- Life cycle impact assessment (LCIA): inventory data were aggregated into impact categories and expressed per functional unit (one ton of seafood produced). LCIA was performed based on the CML baseline 2000 method (Guinée et al., 2002) and environmental impacts were calculated using SimaPro® 8.0 software (Pré Consultants, 1997). We selected eleven of the most commonly used impact categories in seafood LCAs:
    - Abiotic Depletion Potential: expressed in kg Sb equivalent (eq) and reflects the decrease in non-renewable and renewable abiotic resources that are available for human use. It is calculated following the equation $\frac{\text{extraction}}{(\text{ultimate reserve})^2}$ and then compared to the referenece abiotic depletion potential of antimony (Sb).
    - Acidification Potential: expressed in kg SO_2 eq and reflects the negative acidic effects on water and soil. It was calculated based on the mean characterization factor for European acidification potential (Huijbregts, 1999).
    - Eutrophication Potential: expressed in kg PO_4 eq and reflects the negative impcts of discharging nitrogen and phosphorus in the environment. It was calculated using characterization factors recommended by Impact World+ (Helmes, 2012).
    - Global Warming Potential: expressed in kg CO_2 eq and reflects the negative impacts of greenhouse gas emissions that increase the absorption of heat-radiation, resulting in the increase of temperature and climate change. It was calculated based on the global warming potential over a 100-year time horizon (GWP100) recommended by the Intergovernmental Panel on Climate Change (IPCC, 2014).
    - Ozone Depletion Potential: expressed in kg of chlorofluorocarbons-11 (CFC-11) and reflects potential damage caused by chlorinated and brominated chemicals, which increase the amount of harmful ultraviolet light hitting the earth’s surface (Hauschild and Wenzel, 1998).
    - Photochemical Oxidant Formation Potential: expressed in kg ethylene (C_2H_4) eq and reflects negative impacts of chemical substances caused by sunlight reacting

to certain fossil fuel emissions. Photochemical oxidants are particularly dangerous to human health and ecosystems (Baumann and Tillman, 2004).

- Human Toxicity Potential: expressed in kg 1,4-dichlorobenzene (1,4-DCB) eq and reflects negative impact caused by chemicals released into water, air or soil on human health. It includes the inherent toxicity of a pollutant and its dose.
- Marine Eco-Toxicity Potential: expressed in kg 1,4-DCB eq and reflects negative impacts generated by toxic substances on marine ecosystems. It was calculated using fate, exposure and effect factors of toxic emissions recommended by USES-LCA method.
- Terrestrial Eco-Toxicity Potential (TETP): expressed in kg 1,4-DCB eq and reflects negative impacts generated by toxic substances on terrestrial ecosystems. It is calculated following the same method as marine eco-toxicity potential.
- Land Occupation Potential: expressed in m^2year and reflects the terrestrial area required to produce the functional unit.
- Total Cumulative Energy Demand: expressed in megajoules (MJ) and reflects the amount of energy (e.g. fossil fuels, electricity) required the functional unit (Verein Deutscher Ingenieure (VDI), 1997). It was calculated using characterization factors equal lower heating values in SimaPro (Pré Consultants, 1997).

In addition, we calculated another impact category for the aquaculture part:

- Net Primary Production use: expressed in kg of Carbon (C) and reflects the amount of C necessary for fish production as a biotic resource (Papatryphon et al., 2004). It includes primary production from terrestrial ingredients (g C per kg of crop dry matter (Tyedmers, 2000)) and marine ingredients ($M9^{-1}$) 10(T-1), with M is the wet weight and T is the trophic levels of marine organisms (Pauly and Christensen, 1995)

We also estimated the impact of both activities on marine seafloor. We used the method proposed by Eigaard et al. (2015) to calculate the seafloor damage related to demersal trawling. We used the Meramod model to refine "sea use" impact category to assess impacts of aquaculture on seabed degradation; this methodology was proposed and developed in Abdou et al. (2017b).

All selected impact categories were calculated for the average demersal trawler and the average aquaculture farm and then compared to each other.

4.2.2.2. Meta-analysis

Meta-analysis is the statistical analysis for synthesizing different outcomes from multiple scientific studies addressing the same research question (Hedges and Olkin, 1985; Koricheva et al., 2013). It was originally developed in medicine and social sciences (Hedges and Olkin, 1985) and then introduced in ecology and biology in the 1990s (Gurevitch et al., 1992; Järvinen, 1991).

Meta-analysis is an informative and powerful statistical tool to summarize and contrast outcomes (effect sizes) of studies on the same topic. It is based on expressing results of each study on a common scale (Koricheva et al., 2013; Rothman et al., 2008). Effect size can be conceptualized as the standardized difference between different studies. Effect size measures can be combined across studies to estimate the grand mean effect size and to test if it has significant difference between studies. Meta-analysis presents several advantages over narrative reviews. Narrative reviews provide experts with interpretations and conclusions; however, they are inherently subjective, especially in the choice of reviewed studies and how to interpret their results. In addition, they do not handle large amounts of data and results could be presented in complicated ways (large tables) that are hard to interpret.

Meta-analysis was carried using Open Meta-analyst for Ecology and Evolution (OpenMEE®) software. It provides an intuitive graphical use interface (GUI) to display the statistical functionalities of the R software (R Core Team, 2016). OpenMEE combines the strengths of GUI-driven user-friendly programs with the statistical sophistication provided by R. Indeed, the main statistical R packages used by OpenMEE are metafor (Viechtbauer and others, 2010) and mvmeta (Gasparrini et al., 2012). In the current study we based the calculation of effect sizes on the raw mean difference between impacts reported in fisheries (5 different studies containing 8 different fishing methods) (Table 4.1) and aquaculture (7 different studies containing 19 different aquaculture activities) (Table 4.2) LCA studies worldwide and the ones for the average demersal trawler and aquaculture farm in Tunisia. The meta-analysis includes all impact categories previously used to compare the environmental performances of both activities in addition to the NPPuse. Additionally, we calculated effect size based on the correlation fuel/environmental impacts (for demersal trawling) and feed conversion ratio (FCR)/environmental impacts (for aquaculture). Correlation coefficients r are transformed into their corresponding Fisher's Z-transformation value. The Z-scores calculation takes into consideration sample sizes and they are considered as effect-sizes in the meta-analysis. A relatively high relative Fisher's Z-score reflects a high positive correlation and vice versa. Fisher's Z-score is commonly used to test the significance of the difference between correlation coefficients through p-value calculation.

Table 4.1 : Fisheries LCA studies included in the meta-analysis.

Fishing gear	Studies	Functional unit (1 ton of)	Location
Offshore demersal trawling	(Vázquez-Rowe et al., 2012c)	Landed fish	Galicia (NWSpain)
Coastal trawling	(Vázquez-Rowe et al., 2012c)	Landed fish	Galicia (NWSpain)
Offshore trawling	Ziegler et al. (2011)	Mauritanians pink shrimps	Senegal
Demersal trawling	Svanes et al. (2011)	Cod loin	Northeast Atlantic
Demersal trawling	Vázquez-Rowe et al. (2011b)	Landed hake	Galicia (NWSpain)
Offshore lining	Vázquez-Rowe et al. (2011b)	Landed hake	Galicia (NWSpain)
Offshore demersal trawling	Ziegler and Valentinsson, (2008)	Norway lobster	Sweden
Creeling	Ziegler and Valentinsson, (2008)	Norway lobster	Sweden

Table 4.2 : Aquaculture LCA studies included in the meta-analysis.

Fishing gear	**Studies**	**Functional unit**	**Location**
Marine net-pen system	Ayer and Tyedmers (2008)	1 ton of Salmonid (*Salmo salar*)	British Columbia (Canada)
Marine floating bag system	Ayer and Tyedmers (2008)	1 ton of Salmonid (*Salmo salar*)	British Columbia (Canada)
Land-based flow-through	Ayer and Tyedmers (2008)	1 ton of Salmonid (*Salmo salar*)	British Columbia (Canada)
Flow-through system	(d'Orbcastel et al., 2009)	1 ton of trout (*Salvelinus fontinalis*)	France
Recirculating system 1	(d'Orbcastel et al., 2009)	1 ton of trout (*Salvelinus fontinalis*)	France
Recirculating system 2	(d'Orbcastel et al., 2009)	1 ton of trout (*Salvelinus fontinalis*)	France
Lake production	Pelletier and Tyedmers (2010)	1 ton of tilapia (*Oreochromis niloticus*)	Indonesia
Pond production	Pelletier and Tyedmers (2010)	1 ton of tilapia(*Oreochromis niloticus*)	Indonesia
Flow-through system	Aubin et al. (2009)	Rainbow trout(*Oncorhynchus mykiss*)	France
Sea-cages	Aubin et al. (2009)	Sea bass (*Dicentrarchus labrax*)	Greece
Recirculating system	Aubin et al. (2009)	Turbot (*Scophtalmus maximus*)	France
Traditional raceway	Jerbi et al. (2012)	Seabass (*Dicentrarchus labrax*)	Tunisia
Cascade raceway	Jerbi et al. (2012)	Seabass (*Dicentrarchus labrax*)	Tunisia
Sea-cages	Pelletier et al. (2009)	Salmon (*Salmo salar*)	Norway
Sea-cages	Pelletier et al. (2009)	Salmon (*Salmo salar*)	UK
Sea-cages	Pelletier et al. (2009)	Salmon (*Salmo salar*)	Canada
Sea-cages	Pelletier et al. (2009)	Salmon (*Salmo salar*)	Chile
Net-cages	Mungkung et al. (2013)	Carp (Cyprinus carpio carpio) and tilapia (Oreochromis niloticus)	Indonesia
Net-cages	Mungkung et al. (2013)	Carp (Cyprinus carpio carpio) and tilapia (Oreochromis niloticus)	Indonesia

4.2.3. Results

4.2.3.1. LCA results comparison

Abiotic depletion potential is lower for the average aquaculture farm (27.5 kg Sb eq t^{-1}) than for the average demersal trawler (93.9 kg Sb eq t^{-1}). The difference is significant ($p < 2.2\ e^{-16}$). The main contributor to this impact is fish feed production (76%) for the aquaculture, and fuel and lubricating oil production (96%) for demersal trawlers (Figure 4.1).

Acidification potential is lower for the average aquaculture farm (22.4 kg SO_2 eq t^{-1}) than for the average demersal trawler (155.8 kg SO_2 eq t^{-1}). The difference is significant ($p < 2.2\ e^{-16}$). For aquaculture, fish feed production contributed most to the acidification potential (78%), followed by fingerling production (10%); fish production was the main contributor to this impact in the case of fishery (83%) followed by diesel and lubricating oil production (14%)(Figure 4.1).

Eutrophication potential is higher for the average aquaculture farm (108.8 kg PO_4 eq t^{-1}) than for the average demersal trawler (9.3 kg PO_4 eq t^{-1}). The difference is significant ($p = 5.3\ e^{-14}$). Eutrophication potential is dominated by fish production in both cases (91% for aquaculture and 57% for fishery), followed by fish feed production (7%) for aquaculture and by diesel and lubricating oil production (33%) for fishery (Figure 4.1).

Global warming potential is lower for the average aquaculture farm (3,937.7 kg CO_2 eq t^{-1}) than for the average demersal trawler (13,773.3 kg CO_2 eq t^{-1}). The difference is significant ($p < 2.2\ e^{-16}$). Fish production contributed by 81% of this impact for demersal trawling; and fish feed production was the main contributor in the case of aquaculture (77%) followed by fingerling production (8%)(Figure 4.1).

Ozone depletion potential is lower for the average aquaculture farm (0.001 kg CFC-11 eq t^{-1}) than for the average demersal trawler (0.003 kg CFC-11 eq t^{-1}). The difference is significant with $p < 2.2\ e^{-16}$. Fish feed production and diesel and lubricating oil production are the main responsible for ozone depletion potential related to aquaculture and demersal trawling with a contribution of 80% and 97%, respectively (Figure 4.1).

Photochemical oxidant formation potential is lower for the average aquaculture farm (0.8 kg C_2H_4 eq t^{-1}) than for the average demersal trawler (2.3 kg C_2H_4 eq t^{-1}). The difference is significant ($p < 2.2\ \mathrm{e}^{-16}$). Photochemical oxidant formation is dominated by fish feed production (74%) for aquaculture, and by diesel and lubricating oil production (55%) and fish production (37%) for demersal trawling (Figure 4.1).

Human toxicity potential is lower for the average aquaculture farm (1,322.7 kg 1,4-DCB eq t^{-1}) than for the average demersal trawler (4,094.7 kg 1,4-DCB eq t^{-1}). The difference is significant ($p < 2.2\ \mathrm{e}^{-16}$). The main contributor to this impact is fish feed production (63%) for aquaculture; and trawler and trawl net construction (57%) and diesel and lubricating oil production (29%) for demersal trawling (Figure 4.1).

Marine ecotoxicity potential is lower for the average aquaculture farm (884,986 kg 1,4-DCB eq t^{-1}) than for the average demersal trawler (1,583,942 kg 1,4-DCB eq t^{-1}). The difference is significant ($p = 1.5\ \mathrm{e}^{-14}$). Fish feed production is the main contributor to this impact (62%), followed by equipment (25%) for aquaculture. Diesel and lubricating oil production is the main contributor (56%), followed by trawler and net construction (30%) for demersal trawling (Figure 4.1).

Terrestrial ecotoxicity potential is lower for the average aquaculture farm (54 kg 1,4-DCB eq t^{-1}) than for the average demersal trawler (88 kg 1,4-DCB eq t^{-1}). The difference is significant ($p < 2.2\ \mathrm{e}^{-16}$). Fish feed production and trawler and trawl net construction are the main contributor to this impact (85%)(Figure 4.1).

Land occupation potential is higher for the average aquaculture farm (911 m^2year t^{-1}) than for the average demersal trawler (119 m^2year t^{-1}). The difference is significant ($p = 3.5\ \mathrm{e}^{-16}$). Fish feed production contributed most to mean land occupation (96%) for aquaculture. For demersal trawling, diesel and lubricating oil production contributed the most (57%) followed by trawler and net construction (30%)(Figure 4.1).

Total cumulative energy demand is lower for the average aquaculture farm (63,246 MJ t^{-1}) than for the average demersal trawler (212,637 MJ t^{-1}). The difference is significant ($p < 2.2\ \mathrm{e}^{-16}$). Fish feed production and diesel and lubricating oil production are the main responsible for this impact with a contribution of 80% for aquaculture and 96% for demersal trawling (Figure 4.1).

The average damage resulted from demersal trawlers in the Gulf of Gabes on seafloor is equal to 1,350,000 $m^2.h^{-1}$. This hourly damage was roughly converted to m^2 t^{-1} (knowing the approximate number of hours of trawling per year and the total production per year) in order to compare to damage resulted from aquaculture farm. Demersal trawling impacts 27,163 m^2 t^{-1}; meanwhile, aquaculture damages only 11,242 m^2 t^{-1}.

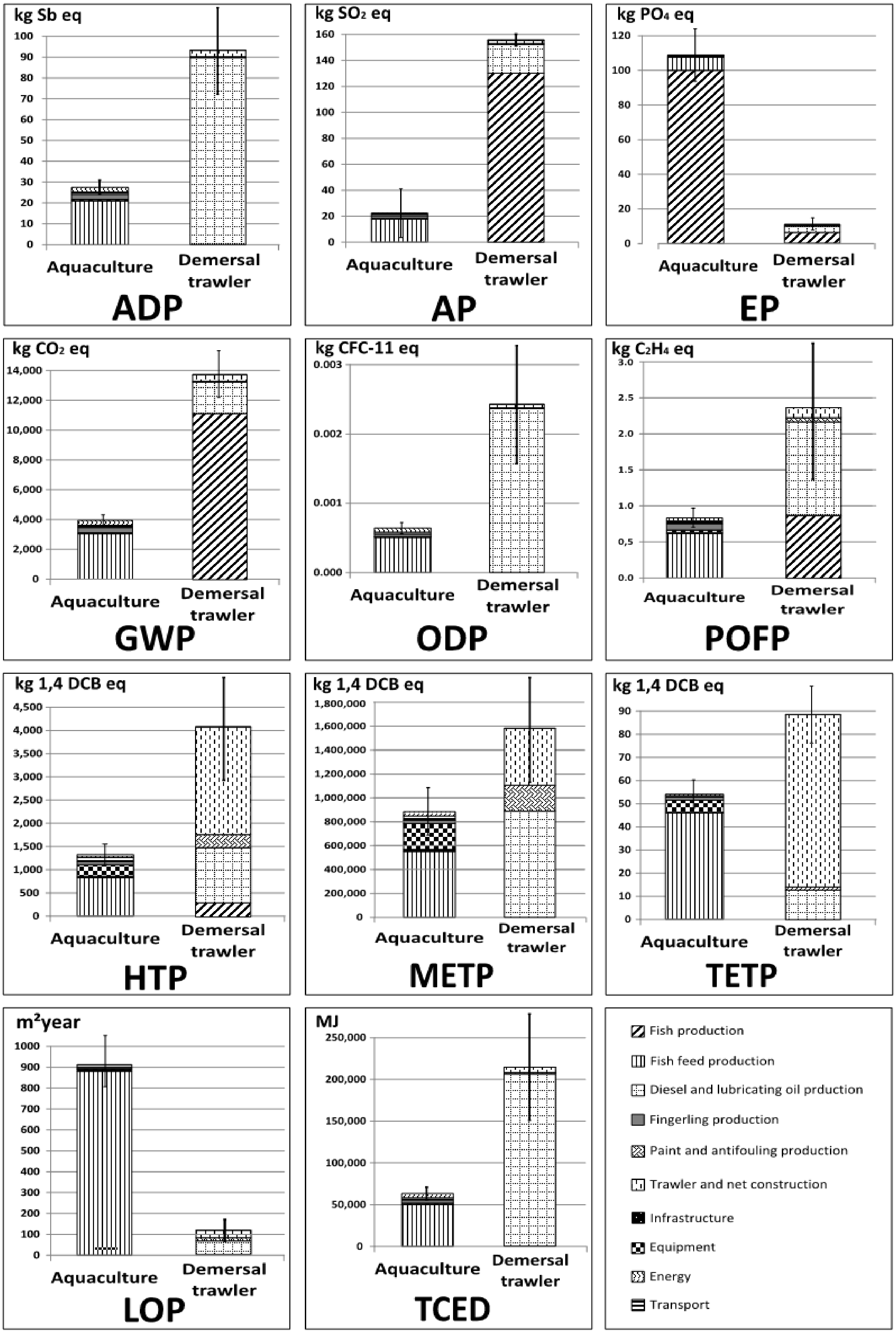
kg Sb eq
Aquaculture
Demersal trawler
ADP
kg SO2 eq
Aquaculture
Demersal trawler
AP
kg PO4 eq
Aquaculture
Demersal trawler
EP
kg CO2 eq
Aquaculture
Demersal trawler
GWP
kg CFC-11 eq
Aquaculture
Demersal trawler
ODP
kg C2H4 eq
Aquaculture
Demersal trawler
POFP
kg 1,4 DCB eq
Aquaculture
Demersal trawler
HTP
kg 1,4 DCB eq
Aquaculture
Demersal trawler
METP
kg 1,4 DCB eq
Aquaculture
Demersal trawler
TETP
m²year
Aquaculture
Demersal trawler
LOP
MJ
Aquaculture
Demersal trawler
TCED
Fish production
Fish feed production
Diesel and lubricating oil prduction
Fingerling production
Paint and antifouling production
Trawler and net construction
Infrastructure
Equipment
Energy
Transport

Figure 4.1 : Comparison of environmental impacts of the average fish farm and average demersal trawler in Tunisia for the production of the functional unit (1 ton of seafood) and contribution of their components to impact categories. Bars represent mean impacts, and error bars represent 1 standard error. ADP = Abiotic Depletion Potential, AP = Acidification Potential, EP = Eutrophication Potential, GWP = Global Warming Potential, ODP = Ozone Depletion Potential, POFP = Photochemical Oxidant Formation Potential, HTP = Human Toxicity Potential, METP = Marine Eco-Toxicity Potential, TETP = Terrestrial Eco-Toxicity Potential, LOP = Land Occupation Potential, TCED = Total Cumulative Energy Demand.

4.2.3.2. Meta-analysis results

4.2.3.2.1. Aquaculture meta-analysis

Mean acidification potential of all studies is 37.28 kg SO_2 eq t^{-1} and the mean difference between impacts of the average sea-cage aquaculture farm in Tunisia and the other studies is 3.25 kg SO_2 eq t^{-1}. The difference between studies is significant ($p < 0.001$). Seabass and seabream reared in cascade raceway and traditional raceway in Tunisia (Jerbi et al., 2012) had the highest acidification impact, 47.6 and 31.6 kg SO_2 eq t^{-1} higher than the average sea-cage farm in Tunisia; followed by turbot reared in recirculating system (25.8 kg SO_2 eq t^{-1} higher t than the average sea-cage farm in Tunisia)(Aubin et al., 2009). Trout in recirculating system in France (d'Orbcastel et al., 2009) had the lowest acidification potential between all studies, with 11.9 kg SO_2 eq t^{-1} less than the average sea-cage farm in Tunisia (Figure 4.2A).

Mean eutrophication potential of all studies is 70.1 kg PO_4 eq t^{-1} and the mean difference between impacts of the average sea-cage aquaculture farm in Tunisia and the other studies is -34.2 kg PO_4 eq t^{-1}. The difference between studies is significant ($p < 0.001$). Seabass and seabream reared in cascade raceway and traditional raceway in Tunisia (Jerbi et al., 2012) had also the highest eutrophication potential among all studies, 106.2 and 71.2 kg PO_4 eq t^{-1} higher than the average sea-cage aquaculture farm in Tunisia (Figure 4.2B).

Mean global warming potential of all studies is 20,628.1 kg CO_2 eq t^{-1} and the mean difference between impacts of the average sea-cage aquaculture farm in Tunisia and the other studies is 6133.4 kg PO_4 eq t^{-1}. The difference between studies is significant ($p < 0.001$). Salmon rearing in sea-cages in Norway and in the UK (Pelletier et al., 2009) has the highest global warming impact, with 123,426.7 and 97,326.7 kg PO_4 eq t^{-1} higher than the average sea-cage aquaculture farm in Tunisia (Figure 4.2C).

Mean total cumulative energy demand of all studies is 89,503.3 MJ and the mean difference between impacts of the average sea-cage aquaculture farm in Tunisia and the other studies is 11769.6 MJ. The difference between studies is significant ($p < 0.001$). Seabass and seabream reared in cascade raceway and traditional raceway in Tunisia (Jerbi et al., 2012) and turbot reared in recirculating system in France had the highest energy demand (Figure 4.2D).

Mean NPPuse of all studies is 50,043.2 kg C eq t^{-1} and the mean difference between impacts of the average sea-cage aquaculture farm in Tunisia and the other studies is -146,0821.1 kg C eq t^{-1} All studies included in the meta-analysis showed lower NPPuse impact than the average sea-cage aquaculture farm in Tunisia (Figure 4.2E).

Mean land occupation potential of all studies is 4,871 m^2year t^{-1} and the mean difference between impacts of the average sea-cage aquaculture farm in Tunisia and the other studies is 3465.2 m^2year t^{-1}. The highest potential was related to the polyculture of carp and tilapia in net cages (practice 1) in Indonesia which was 14,563 m^2year t^{-1} higher than the average sea-cage aquaculture farm in Tunisia (Figure 4.2F).

In addition to the average sea-cage aquaculture farm in Tunisia, human and marine toxicity potential are only considered for three salmonid aquaculture practices (Ayer and Tyedmers, 2008). The mean difference between human toxicity of the average sea-cage aquaculture farm in Tunisia and the other studies is -441.5 kg 1,4-DCB eq t^{-1} (Figure 4.3G) and between marine toxicity of the average sea-cage aquaculture farm in Tunisia and the other studies is -375,489.5 kg 1,4-DCB eq t^{-1}(Figure 4.2H).

Meta-analysis using correlation coefficients and Fisher's Z-score as effect size showed a positive correlation between FCR and acidification, eutrophication and energy demand. We also noticed a negative correlation between FCR and global warming potential and the NPPuse. However, the correlation between FCR and the impact categories is not significant ($\mathrm{p} = 0.107$). The mean Z value is 0.1 (Figure 4.3).

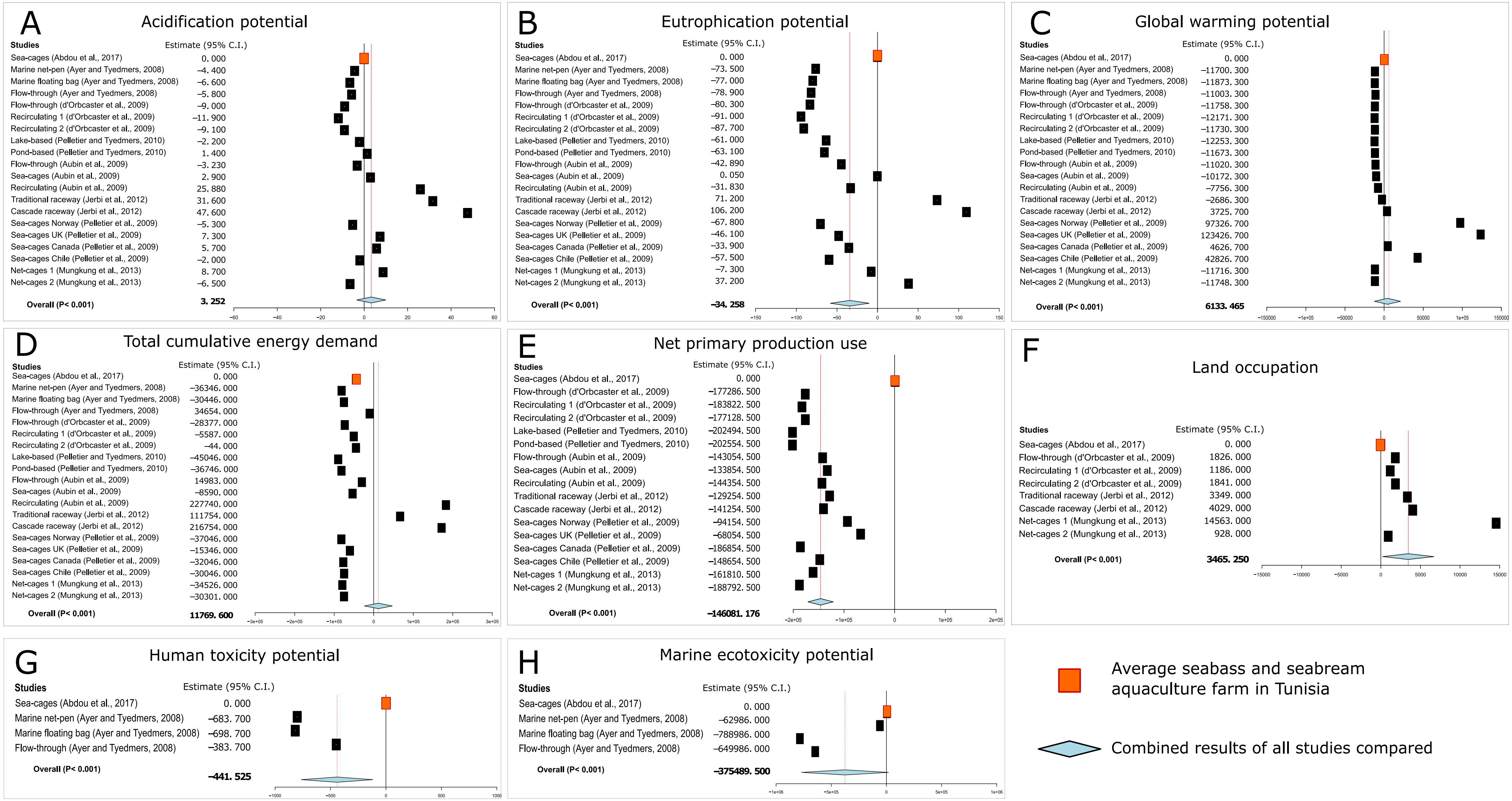

Figure 4.2 : Meta-analysis forest plot for the comparison of aquaculture LCA studies with the average aquaculture farm in Tunisia using the software OpenMEE and mean difference between impact categories as effect size.

Impact categories	Estimate (95% C.I.)
Acidification potential	0.241
Eutrophication potential	0.476
Global warming potential	-0.020
Total cumulative energy demand	0.081
Net primary production use	-0.246
Overall (P=0.256)	**0. 107**

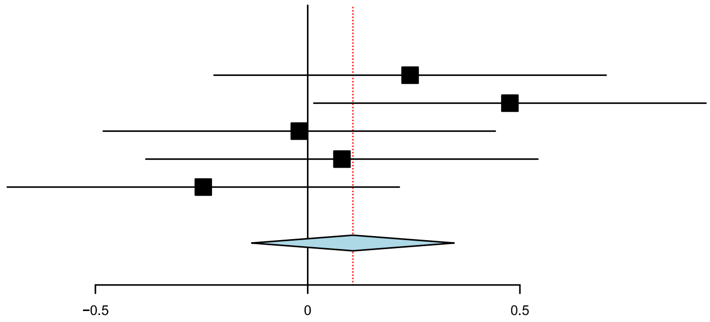

Figure 4.3 : Meta-analysis forest plot of aquaculture LCA studies using the software OpenMEE. Fisher's Z-score between FCR and impacts as effect size.

4.2.3.2.2. Demersal trawling meta-analysis

Mean abiotic depletion potential of all studies is 78.7 kg Sb eq t^{-1} and the mean difference between impacts of the average demersal trawler in Tunisia and the other studies is 15.2 kg Sb eq t^{-1}. Demersal trawling in Sweden (Ziegler and Valentinsson, 2008) have the highest abiotic depletion potential (106.1 kg Sb eq t^{-1} higher than the average demersal trawler in Tunisia)(Figure 4.4A).

Mean acidification potential of all studies is 125.9 kg SO_2 eq t^{-1} and the mean difference between impacts of the average demersal trawler in Tunisia and the other studies is -29.8 kg SO_2 eq t^{-1}. The average demersal trawler in Tunisia was the third highest between all studies; the highest is demersal trawling in Senegal (Ziegler et al., 2011) followed by demersal trawling in Sweden (Ziegler and Valentinsson, 2008). Coastal trawling in Galician fisheries has the lowest acidification (128.6 kg SO_2 eq t^{-1} lower than the average demersal trawler in Tunisia) (Figure 4.4B).

Mean eutrophication potential of all studies is 25.9 kg PO_4 eq t^{-1} and the mean difference between impacts of the average demersal trawler in Tunisia and the other studies is 16.6 kg PO_4 eq t^{-1}. Demersal trawling in Sweden has the highest eutrophication potential (71.7 kg PO_4 eq t^{-1} higher than the average demersal trawler in Tunisia) (Figure 4.4C).

Mean global warming potential of all studies is 14,650.1 kg CO_2 eq t^{-1} and the mean difference between impacts of the average demersal trawler in Tunisia and the other studies is -876.813 kg CO_2 eq t^{-1} (Figure 4.4D). Demersal trawlers in Sweden (Ziegler and Valentinsson, 2008) and in Senegal (Ziegler et al., 2011) had the lowest global warming potential (21,226.6 and 17,926 kg CO_2 eq t^{-1} less than the average demersal trawler in Tunisia, respectively).

Mean ozone depletion potential of all studies is 0.051 kg CFC-11 eq t^{-1} and the mean difference between impacts of the average demersal trawler in Tunisia and the other studies is 0.048 kg CFC-11 eq t^{-1}. Senegalese demersal trawlers (Ziegler et al., 2011) had the highest ozone depletion impact (0.267 kg CFC-11 eq t^{-1} higher than the average demersal trawler in Tunisia) followed by demersal trawlers in Northeast Atlantic (Svanes et al., 2011) (0.055 kg CFC-11 eq t^{-1} higher than the average demersal trawler in Tunisia)(Figure 4.4E).

Mean marine ecotoxicity of all studies is 1,865,388.7 kg 1,4-DCB eq t^{-1} and the mean difference between impacts of the average demersal trawler in Tunisia and the other studies is 281,446.2 kg 1,4-DCB eq t^{-1}. The highest marine toxicity potential was noted for demersal trawlers in Sweden (Ziegler and Valentinsson, 2008) with 3,316,057.5 kg 1,4-DCB eq t^{-1} higher than the average demersal trawler in Tunisia (Figure 4.4F).

In addition to the average demersal trawler in Tunisia, total cumulative energy demand was only included in two other studies. Mean energy demand between the three studies is 258,879 MJ and the mean difference between impacts of the average demersal trawler in Tunisia and the other two studies is 46,241 MJ (Figure 4.4G).

Meta-analysis using correlation coefficients and Fisher's Z-score as effect size showed a positive strong correlation between fuel quantity and abiotic depletion, acidification, eutrophication, global warming, energy demand and ozone depletion. The Z value ranges between 1.17 and 2.80. There is a weak positive correlation between fuel and marine ecotoxicty and photochemical oxidant formation (z equal to 0.18 and 0.06, respectively). The mean Z value is equal to 1.5 and the correlation between fuel and impact categories is significant with and overall $p < 0.001$ (Figure 4.5).

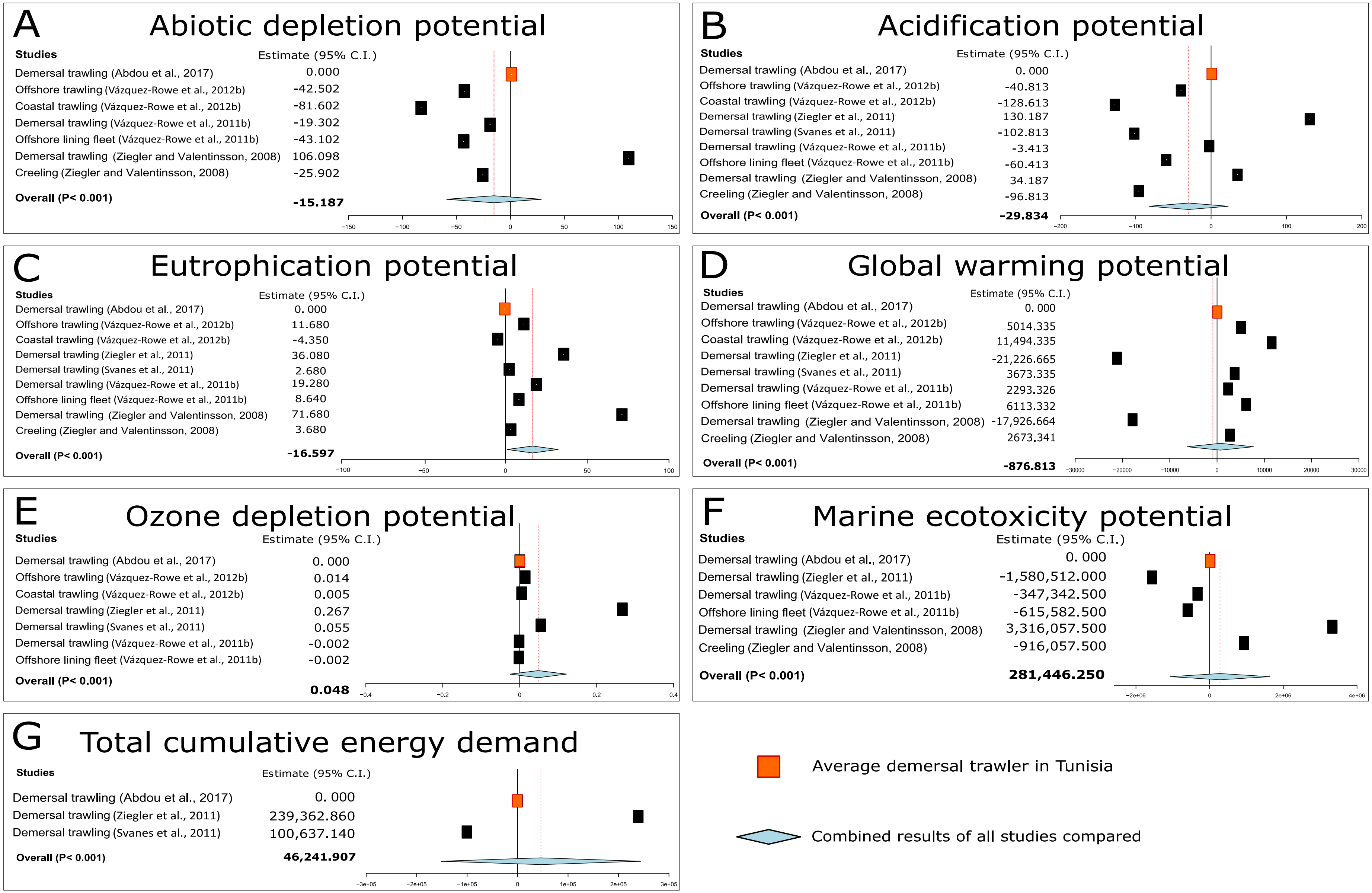

Figure 4.4 : Meta-analysis forest plot for the comparison of fisheries LCA studies with the average demersal trawler in Tunisia using the software OpenMEE and mean difference between impact categories as effect size.

Impact categories	Estimate (95% C.I.)
Abiotic depletion potential	2. 752
Acidification potential	1. 603
Eutrophication potential	1. 171
Global warming potential	2. 058
Total cumulative energy demand	2. 814
Marin eco-toxicity potential	0. 184
Ozone depletion potential	1. 182
Photochemicaloxidantformationpotential	0. 063
Overall (P< 0.001)	**1. 478**

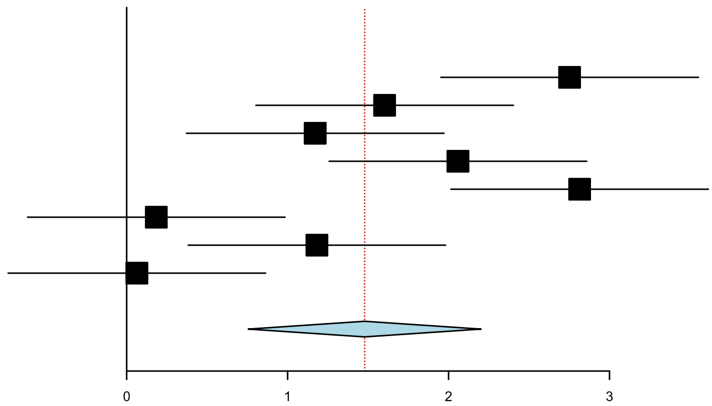

Figure 4.5 : Meta-analysis forest of fisheries LCA studies using the software OpenMEE. Fisher's Z-score between fuel consumption and impacts as effect size.

4.2.4. Discussion

Predictions state that aquaculture will compensate the stagnating supply of fish provided by fisheries (Brugère and Ridler, 2004; Delgado et al., 2003). The substantial growth of aquaculture could be beneficial to fisheries by relieving the pressure on several fish stocks; however, relying on fish-derived ingredient is seen as unsustainable from ecological perspective and could represent a hindering factor for the long-term expansion of this activity (Natale et al., 2013). Even though aquaculture and demersal trawling are different production systems, their environmental impacts can be compared using LCA framework. In fact, both fish production systems produce different species but they are interacting on a socio-economic perspective at the level of the global food market and at the level of the aqua feed market. However, aquaculture is still to exploit its full potential to increase productivity through the domestication of new species (Duarte et al., 2007), genetics, genomics and selective breeding (McAndrew and Napier, 2011), and it started to more and more substitute fish produced by fisheries through the intensification of aquaculture production systems (Asche, 2008). The expansion of aquaculture in respect to fisheries represents a transition from hunting to farming (Natale et al., 2013).

From an LCA viewpoint, aquaculture activity in Tunisia had higher eutrophication impact and a higher use of land surface than demersal trawling. Fish production phase contributed most to mean eutrophication potential. This is explained by the emissions of nutrient related to rearing practices and fishing onboard activities. Eutrophication generated from demersal trawling is mainly related to emissions of nitrous substances from combustion of fuel. However, eutrophying emissions per functional unit are higher in the case of aquaculture farming than demersal trawling. Fish feed efficiency in aquaculture farms is directly related to technical strategies and the FCR. Indeed, high FCR reflects a low efficiency of feed use and implies that large amount of uneaten and undigested feed are emitted into water and result in increasing the eutrophication potential. Therefore, it is crucial to improve the feeding practices, feed distribution methods and ration calculation in order to reduce the FCR of fish farms and consequently environmental impacts. The meta-analysis revealed that the average Tunisian sea-cage aquaculture farm had the fourth highest eutrophication potential amongst all studies, which can be explained by the difference in fish feed content and ingredients in addition to the technical strategies adopted. Other aquaculture systems with lower eutrophication impact had better fish stock management and rationing and consequently a better FCR. Aquaculture in Tunisia had a higher land occupation impact than demersal trawling, and the exclusive contributor to this impact is the fish feed production due to the use of crop-based ingredients which requires large terrestrial areas (Mungkung et al., 2013). Terrestrial surface is only required in demersal trawling for the production of diesel and lubricating oil and for the construction of trawler and trawl net. However, seafloor damaged surface was higher for demersal trawling activity than aquaculture farms. Impacts of aquaculture on seafloor are essentially related to nutrient release into water under fish farms. Nutrient loading may negatively influence sensitive ecosystems (Marbà et al., 2006) and benthic communities (Karakassis, 2000), however, in some cases it can have a positive impacts by increasing the productivity of the ecosystem (Machias et al., 2004). In addition to physical disturbance of habitats (Cook et al., 2013) , demersal trawlers impact seafloor and communities by causing mortality of benthic invertebrates (Kaiser et al., 2006) and resuspension of sediments (Martín et al., 2014) which on the long-term may result in changes in species composition (Kaiser et al., 2006) and reduction in habitat complexity (Kaiser et al., 2002). Meta-analysis showed that Tunisian aquaculture had the lowest land occupation impact among all studies; however other fisheries LCAs did not consider these two impact categories.

In addition to eutrophication and land occupation, the fish production phase was the major contributor to acidification, global warming and photochemical oxidant formation related to demersal trawling. However, those three impacts were higher for trawling than aquaculture in Tunisia. This important contribution of fish production is explained by the emission of substances due to fuel combustion (Avadí and Fréon, 2013b). The three impacts were dominated by fish feed production in the case of aquaculture, which is related to the presence of high amounts of fish meal and fish oil as fish feed ingredients. The meta-analysis showed that most demersal trawling LCAs had high acidification potential than other fisheries because it is the most fuel-intensive fishing method (Avadí and Fréon, 2013b; Schau et al., 2009). Acidification and global warming potential related to aquaculture in Tunisia was similar to most of the other studies. Seabass and seabream reared in cascade raceway and traditional raceway in Tunisia (Jerbi et al., 2012) showed the highest acidification impact which is related to the relatively high FCR in those aquaculture systems and high energy use.

Demersal trawling had higher impact intensity for the other six impact categories. Abiotic depletion, ozone depletion, marine ecotoxicity and total cumulative energy demand were dominated by the fuel and lubricating oil production. This finding is consistent with previous fishery LCAs (Avadí and Fréon, 2013b; Schau et al., 2009; Vázquez-Rowe et al., 2011c). Those impacts are higher for trawling due to the low energy efficiency of the fishing gear used. Construction of vessels and trawling nets are the major contributors to the last two impact categories (human and terrestrial toxicity). This finding is contrary to what was published before; construction phase was excluded from most of seafood LCA studies because it was found to have negligible contribution to environmental impacts (Avadí and Fréon, 2013b; Ziegler et al., 2003).

The major contributor to most impact categories studied is fish feed production in the case of aquaculture. The heavy influence of fish feed is not only related to its production, but also to the collection of ingredients (mainly fish meal and fish oil). Aquaculture share of global fishmeal and fish oil greatly increased over the last decade to 68% and 88%, respectively (Tacon and Metian, 2008). Indeed, 36% of global landings from fisheries are used for the production of fishmeal and fish oil. Given the fact that most marine resources are finite, the main concern arises from the increased share of fish meal and fish oil use is that aquaculture demand for fish meal and fish oil is no longer sustained by the livestock industry (Delgado et al., 2003); which will result in the increase of prices of these products and create incentive for overfishing (Naylor et al., 2009). Therefore, it is important to reduce the dependency of aquaculture on fish-based feed and search for alternatives to fish-derived ingredients in order to help improving the environmental performance of aquaculture (Dias et al., 2009). The alternative ingredient must have specific nutritional characteristics and must be easy to handle, to ship and to use in feed production (Naylor et al., 2009). Using plant-based ingredients could reduce environmental impacts and decrease dependence and pressure on wild fish stocks (Papatryphon et al., 2004); however, plant feedstuffs have worse digestibility than fish-based ingredients, resulting in higher levels of fish excretion and waste. Therefore, using seafood by-products represent an attractive solution to release the pressure on forage fisheries and to meet the high demand of fish meal and fish oil (Naylor et al., 2009). However, this can possibly lead to a shift in environmental impacts, resulting in higher land occupation potential and energy use (Mungkung et al., 2013). It was demonstrated that in salmonid aquaculture farms, energy consumption related to fish feed with high content of plant-based ingredients is similar to that to produce fish feed using fishery-derived ingredients. In addition, the inclusion of plant-based ingredients did only result in the increase of land occupation and terrestrial ecotoxicity, and it did not affect other environmental impacts (Boissy et al., 2011).

For demersal trawlers, improvements should focus principally on improving the efficiency of fuel use (Vázquez-Rowe et al., 2011c). It is necessary to enhance the skills and the experience of the vessel crew, which can be achieved by using modern technologies and new electronic methods to better select fishing grounds. Improving the fuel quality is also important in order to improve the environmental performance of the demersal trawlers. In fact, replacing fossil fuels with biofuels can decrease CO_2 emissions. Other improvements could be made in the construction phase of the trawlers. Changing the hull shape can result in the increase of energy efficiency up to 20% (Schau et al., 2009). The use of electric fuel injection engines may also improve the combustion and consequently reduce fuel consumption (Woodyard, 2009).

It is important to develop sustainable aquaculture and fisheries to meet sustainable development goals; namely, goal 2 (end hunger, achieve food security, improve nutrition and promote sustainable agriculture) and goal 12 (ensure sustainable consumption and production patterns). The meta-analysis showed a significant correlation between fuel consumption and impact categories in all fisheries included in the study. Therefore, management measures must focus on reducing fuel consumption per ton of seafood produced (Vázquez-Rowe et al., 2011a). Fuel use is influenced by the characteristics of the fisheries (e.g. targeted stocks, fishing gear, fishing zones, number of fishing trips) in addition to the experience and the skills of the vessel crew. It is also important to improve the fuel quality itself by replacing fossil fuels with biofuels. Aquaculture farms must focus of improving the feed-use efficiency, which will decrease the environmental impacts and maintain economic profitability (Papatryphon et al., 2004). This could be achieved though better stock-management practices (controlling the size and number of fish) and efficient feeding practices (e.g. timing and method of distributing feed pellets)(Cripps and Bergheim, 2000).

At first glance, aquaculture appears to be more input demanding; however, demersal trawlers are extracting natural resources with intensive consumption of fuel. Aquaculture is characterized by transforming feed into fish in a controlled environment by property rights (Natale et al., 2013). Additionally, feed efficiency of farmed fish is higher than in wild captured fish, which can explain the lower environmental impact of aquaculture compared to demersal trawling (Tidwell and Allan, 2001). Results obtained from LCAs studies are valuable to identify the key processes to enhance the environmental performance and the long-term sustainability of aquaculture and demersal trawling. This analysis would be improved by including specific impact categories to capture additional environmental, economic and/or social characteristics related to seafood production systems. It would be beneficial to extend boundaries of the studied systems to become "cradle-to-grave" study.

4.2.5. Conclusion

This study provides assessment of environmental performance associated with the landing of 1 ton of seafood by demersal trawlers and one ton of of seabass and seabream produced on a sea-cage aquaculture farm in Tunisia. Based on this study, we can conclude that both aquaculture and demersal trawling cause environmental impacts on a local and global scale. The study revealed that demersal trawling in Tunisia had higher abiotic depletion potential, acidification, global warming potential, ozone depletion potential, photochemical oxidant formation potential, human toxicity, marine ecotoxicity, terrestrial ecotoxicity, total cumulative energy demand ad seafloor damage than aquaculture farms. Only eutrophication and land occupation were higher for aquaculture than demersal trawling. LCA showed that impacts related to demersal trawling are mainly related to onboard activity and the production of fuel and lubricating oil. Thus, it is important to minimize the fuel consumption per ton landed in order to improve the environmental performance of this sector. Rearing practices and fish feed production are responsible for most impacts of aquaculture activity in Tunisia; this is related to the large amounts of nutrients released into the environment. Therefore, the optimization of fish feed use and production would decrease the FCR and positively influence the environmental performance of this sector.

4.3. Conclusion et perspectives du chapitre

Dans ce chapitre nous avons comparé le bilan environnemental de la production d'une tonne de produits de la mer provenant de la pêche au chalutage de fond et celle provenant de l'élevage de poissons (bar et daurade) dans des cages en mer en Tunisie. Les résultats pour la Tunisie ont ensuite été comparés aux résultats pour d'autres méthodes de pêche et d'autres systèmes d'élevage de poisson en utilisant la méthode statistique de la méta-analyse.

Les résultats de ce chapitre révèlent que l'aquaculture en Tunisie a un potentiel d'eutrophisation plus élevé que la pêche. Ceci est directement lié aux émissions importantes de nutriments, rejets de fécès et d'aliment non-consommé. L'occupation des surfaces terrestres est plus importante dans l'aquaculture que la pêche. Le contributeur exclusif à cette catégorie d'impact est la production de l'aliment pour poisson, qui contient des ingrédients d'origine agricole. Les autres impacts étudiés sont plus accentués pour le chalutage de fond.

La méta-analyse des différentes études a montré que la pêche au chalutage de fond en Tunisie a un impact sur l'épuisement des ressources abiotiques et sur le réchauffement climatique plus élevé que les impacts signalés pour les autres études. Cependant, l'impact sur l'eutrophisation et l'appauvrissement de la couche d'ozone est plus faible pour le chalutage de fond en Tunisie que pour les autres études. L'activité aquacole en Tunisie a un impact moins élevé sur l'acidification et l'occupation des surfaces terrestres que les impacts rapportés dans les autres études, mais un impact sur l'eutrophisation plus élevé que dans les autres cas. La méta-analyse pour les activités de pêche a également montré qu'il y a une forte corrélation entre la consommation de carburant et plusieurs catégories impacts étudiées, les plus corrélées sont l'épuisement des ressources abiotiques, la demande d'énergie cumulée et le réchauffement climatique, suivies par l'acidification, l'eutrophisation et l'appauvrissement de la couche d'ozone. D'autre part, la méta-analyse pour les activités aquacoles a montré que la corrélation entre le facteur de conversion d'aliment et l'intensité des impacts sur l'environnement n'est pas forte.

La précision des résultats obtenus dans cette étude peut être améliorée si plus de données actualisées étaient disponibles, ceci permettrait de mener des ACV plus complètes en incluant les étapes de post-production. De plus, l'analyse peut être améliorée en établissant des catégories d'impacts spécifiques et mieux adaptées à l'activité de pêche et d'aquaculture. Ces catégories devront prendre en considération les aspects économique, social et environnemental reliés au secteur de production des produits de la mer.

Malgré le fait que l'activité aquacole demande plus d'intrants, l'aquaculture permet de produire du poisson dans un environnement mieux contrôlé comparé à la pêche qui s'appuie sur l'extraction des ressources halieutiques directement du milieu naturel en consommant des quantités importantes de carburant.

Conclusion générale et perspectives

Les écosystèmes marins sont des systèmes dynamiques ayant une forte variabilité causée par des phénomènes naturels et/ou anthropiques. Au cours des dernières décennies, les pressions exercées par l'homme sur l'environnement marin ont fortement augmenté générant des évolutions importantes dans les écosystèmes marins et dans leurs usages. Parmi les activités humaines, les pressions exercées par la pêche et l'aquaculture sont grandissantes à cause de l'augmentation de la demande mondiale en produits de la mer. Par conséquence, la pêche et l'aquaculture engendrent des impacts directs sur les ressources marines exploitées mais aussi des impacts indirects sur les habitats et l'environnement marin. L'enjeu est donc de placer ces deux activités dans le contexte du développement durable, en améliorant leurs rentabilités économiques, leurs attractivités sociales, et leurs performances environnementales. Du fait d'une forte problématique liée aux pressions anthropiques sur l'environnement marin, l'approche écosystémique des pêches et de l'aquaculture émerge comme une approche pertinente pour assurer une gestion holistique des écosystèmes marins en favorisant l'utilisation durable et équitable de leurs ressources.

L'analyse de la durabilité environnementale évolue de plus en plus vers une approche holistique pour mettre en place d'un modèle de gestion ayant pour but de développer des produits sains et sûrs pour l'homme et l'environnement, et réutilisables ou dégradables. L'analyse du cycle de vie (ACV) est une méthode adéquate à cet effet. Dans le cadre de cette thèse, l'ACV a été adaptée et appliquée à la pêche et l'aquaculture en Tunisie pour déterminer les impacts environnementaux et proposer des moyens d'amélioration des deux activités pour les placer dans le contexte de développement durable.

Dans ce chapitre les principaux résultats de ce travail seront synthétisés, discutés des limites de la méthode d'ACV et son application en Tunisie et des perspectives de recherches potentielles pour compléter ces travaux seront proposées.

1. Synthèse des principaux résultats

Dans ce travail de thèse, le choix de l'ACV comme méthode d'évaluation environnementale a été conditionné par plusieurs critères. L'un des points forts de l'ACV est son aptitude à calculer des impacts à la fois pour toutes les consommations de ressources et les émissions nécessaires à chaque étape de production. En effet, l'ACV permet de passer d'un cadre d'évaluation environnementale antérieure (basée simplement sur les émissions des rejets dans l'écosystème marins) à une approche systémique (prenant en compte toutes les étapes qui interviennent dans la production). Donc le système de production n'est plus uniquement responsable des impacts directs de son activité sur les écosystèmes locaux, mais aussi des impacts liés aux choix pris en termes d'intrants et leurs impacts sur tous les écosystèmes. Un deuxième avantage de la méthode d'ACV est la proposition d'une panoplie de catégories d'impacts calculées sur la base de la même référence, qui est l'unité fonctionnelle. Ainsi, l'ACV permet le passage d'une approche monocritère à une approche multicritère (différents impacts) et multi-étapes (différentes étapes de production) permettant de répondre à différentes questions environnementales que posent les systèmes de production de produits de la mer par pêche et par aquaculture.

Dans le contexte socio-économique actuel, le développement de la pêche et de l'aquaculture dans le contexte de développement durable représente une priorité en Tunisie. Dans le chapitre 2, l'ACV a été appliquée à l'activité aquacole en Tunisie. L'objectif était d'évaluer les modifications environnementales causées par cette activité et de formuler des recommandations pour diminuer les impacts environnementaux. La première étape était d'appliquer l'ACV à toutes les fermes aquacoles spécialisées dans l'élevage du bar et de la daurade dans des cages en mer. Ensuite, la même méthodologie a été appliquée à une seule ferme aquacole en ajoutant une nouvelle catégorie d'impact qui reflète les impacts sur les fonds marins. Ce chapitre a révélé que le niveau d'impact ne dépend pas de la productivité des fermes aquacoles, mais de l'aliment aquacole et des pratiques d'élevage. L'aliment est le premier responsable de la plupart des impacts de production de poisson par aquaculture, ce qui est expliqué par l'utilisation intensive de farine et d'huile de poisson dans la fabrication de l'aliment, responsable des émissions importantes d'azote et du phosphore dans l'environnement. Ceci révèle l'importance de l'optimisation de la formulation de l'aliment pour poissons pour assurer la durabilité du secteur aquacole. Il est important de substituer la farine et de l'huile de poisson par des ingrédients d'origines végétales ce qui permet de diminuer la pression sur les ressources halieutiques (Boissy et al., 2011). Par contre, il faut tenir compte du transfert d'impact vers le compartiment terrestre et la concurrence entre l'alimentation animale et l'alimentation humaine (comme dans le cas des élevages terrestres). Le deuxième chapitre a également montré que les caractéristiques techniques qui influencent le plus l'intensité des impacts environnementaux sont : le ratio de conversion alimentaire, la profondeur sous les cages aquacoles et la taille des cages utilisées pour l'élevage. En plus, la différence entre les bilans environnementaux de l'élevage du bar et de la daurade en Tunisie n'est pas significative. Ces résultats ont mis en évidence l'importance d'adopter de bonnes pratiques d'élevage et des stratégies efficaces d'alimentation de poissons en élevage (distribution d'aliments, rationnement efficace, bonne gestion des stocks de poissons, etc). Il faut aussi que les les autorités encouragent les fermes aquacoles à diminuer leur ratio de conversion d'aliments pour assurer la durabilité du secteur et améliorer leurs performances environnementales. Il faut aussi privilégier et accorder des licences à des fermes ayant des cages plus larges et une profondeur d'eau importante sous les cages.

Le chapitre 3 est consacré à l'analyse environnementale de l'activité de pêche au chalutage de fond dans le Golfe de Gabès. Les résultats ont montré que les impacts de cette activité sont directement proportionnels à la quantité de carburant nécessaire pour la production de produit de la mer. Ceci est lié à l'efficacité d'utilisation du carburant. Le premier responsable de l'impact environnemental dans le cas de chalutage de fond est l'activité à bord des chalutiers (phase de production de poissons), suivi par la production du carburant et de l'huile lubrifiante. Il est donc indispensable d'améliorer l'efficacité d'utilisation d'énergie pour diminuer les impacts environnementaux des chalutiers de fond dans le Golfe de Gabès et diminuer la consommation du carburant par tonne de produit de la mer. Pour atteindre ces objectifs, il faut améliorer les pratiques de pêche ; par exemple, l'utilisation des moyens électroniques pour mieux sélectionner les zones de pêche au lieu de se baser sur la méthode du "bouche-à-oreille". En plus, l'utilisation des systèmes électroniques d'injection de carburant et le changement de la forme de la coque des chalutiers et le type de moteur peuvent augmenter l'efficacité d'utilisation de carburant et diminuer ainsi les impacts environnementaux de l'activité. Enfin, le remplacement du carburant fossile par du biocarburant permet la diminution des émissions de CO_2 et par conséquent la diminution des impacts environnementaux. Malgré les avantages de l'ACV, cette méthode ne prend pas en compte la composante écologique de l'écosystème. Pour remédier à cette lacune, un modèle Ecopath with Ecosim (EwE) a été utilisé pour calculer des indicateurs écosystémiques. Ces indicateurs décrivent l'état de l'écosystème et ses interactions avec l'activité de pêche. Ils ont servi pour compléter l'analyse environnementale de la pêche au chalutage de fond par une analyse écosystémique. Ensuite, le module Ecospace d'EwE été utilisé pour évaluer les conséquences environnementales et écosystémiques de différentes mesures de gestion simulées dans le Golfe de Gabès. Ces mesures de gestion portent sur l'implémentation des aires marines protégées, la prolongation de période de repos biologique et la diminution du nombre de chalutiers de fond. Les résultats ont montré que la prolongation de la période de repos biologique (six mois au lieu de trois) est la mesure de gestion la plus efficace sur le plan environnemental et écosystémique. Ces analyses peuvent être utilisées par les autorités pour déterminer les mesures de gestion les plus adaptées et efficaces dans le Golfe de Gabès.

Une comparaison des impacts environnementaux de la pêche et de l'aquaculture en Tunisie a été conduite dans le chapitre 4. Les résultats ont révélé, bien que l'aquaculture demande plus d'intrants, son bilan environnemental est meilleur que celui de la pêche pour la majorité de catégories d'impacts étudiées. Ceci est est dû au niveau de contrôle élevé de l'activité aquacole par rapport à la pêche au chalutage de fond qui prélève les ressources halieutiques directement du milieu naturel en consommant des quantités importantes de carburant. L'aquaculture en Tunisie a un potentiel d'eutrophisation et d'utilisation de surfaces terrestres plus élevé que la pêche, ce qui directement lié aux émissions importantes de nutriments provenant de l'aliment aquacole et à l'utilisation d'ingrédients d'origine agricole pour sa fabrication. Ensuite, les résultats d'impacts environnementaux calculés pour la Tunisie ont été comparés aux résultats d'impacts pour d'autres méthodes de pêche et d'autres systèmes d'élevage de poisson en utilisant la méta-analyse. Les résultats de la méta-analyse ont montré que l'élevage du bar et de la daurade dans des cages en mer en Tunisie présente un impact sur l'acidification et l'occupation des surfaces terrestres moins élevé que les autres études, mais l'impact sur l'eutrophisation est plus élevé que dans les autres cas. Pour la pêche au chalutage de fond en Tunisie, les résultats de l'épuisement des ressources abiotiques et le réchauffement climatique sont plus élevés que ceux signalés dans les autres études. Par contre, l'impact sur l'eutrophisation et l'appauvrissement de la couche d'ozone est plus faible pour le chalutage de fond en Tunisie que les autres études. Cette analyse indique également une forte corrélation entre la consommation de carburant et la plupart des catégories d'impact étudiées, notamment l'épuisement des ressources abiotiques, la demande d'énergie cumulée et le réchauffement climatique.

2. Les limites de l'ACV

Le cadre méthodologique de l'ACV a été mis en place pour quantifier l'utilisation des ressources et les émissions polluantes dans le secteur industriel. Malgré le fait qu'il s'agit d'une méthode robuste d'évaluation des charges environnementales associées au cycle de vie des produits et processus, son aptitude à couvrir le large éventail des impacts environnementaux liés à la production de produits de la mer présente encore plusieurs lacunes. Pour cela, l'évaluation environnementale des systèmes de production de produits de la mer (pêche et aquaculture) ne peut pas se cantonner à des critères de performance inféodés aux processus industriels. Il est important d'élargir le spectre de l'analyse environnementale pour prendre en compte des indicateurs décrivant les liens qui existent entre les activités de la pêche et de l'aquaculture, et les écosystèmes. Pour remédier à ces lacunes, plusieurs catégories d'impacts et indicateurs ont été développées pour inclure les spécificités de la pêche et de l'aquaculture dans l'ACV.

2.1. Valeurs de référence

Une lacune majeure dans l'ACV des produits de la mer est le manque de valeurs de référence pour fixer les seuils et les limites de durabilité. Les valeurs de référence sont indispensables pour pouvoir juger si l'intensité d'un impact donné est basse ou élevée et si elle est acceptable ou pas. Actuellement, les études ACV des produits de la mer ont recours à la comparaison des résultats avec d'autres systèmes de production des produits de la mer, ce qui pose un problème de comparabilité entre les études. En effet, les études en ACV peuvent avoir des hypothèses de base extrêmement différentes (limites et objectifs des études, méthodes de calculs, règles d'allocation, etc). Dans cette optique, l'identification de gammes de valeurs seuils semble être une priorité pour l'amélioration des ACV des produits de la mer, mais cela nécessite une standardisation internationale de la méthode qui va au-delà du cadre ISO.

2.2. La qualité des données et hypothèses de base

Les résultats de l'ACV sont particulièrement dépendants des hypothèses choisies au début de l'étude. La définition du champ d'étude est nécessaire dans les ACV afin d'inventorier tous les impacts à l'intérieur de ce périmètre. Même si restreindre le champ d'étude permet de mieux cerner les impacts environnementaux, ceci peut nuire à la fiabilité et la précision des résultats. Les résultats de l'ACV dépendent également du choix de l'unité fonctionnelle et de la règle d'allocation. L'allocation en ACV est la répartition de la charge environnementale entre les différents coproduits (produits issus d'un même processus de production ou de transformation). L'ISO a proposé un ordre de priorité d'utilisation des méthodes d'allocation (voir chapitre 1 prgraphe 1.2). La sélection des catégories d'impacts couvertes dans l'étude est un facteur crucial dans l'ACV, il est important de choisir les catégories d'impacts les plus adéquates selon le système étudié et les objectifs de l'étude. Il est donc préconisé d'adopter le principe de parcimonie en limitant le nombre des catégories étudiées pour des raisons de faisabilité et faire le compromis entre la lisibilité des résultats et la complexité de l'analyse environnementale.

La qualité de l'analyse environnementale est tributaire de la qualité des données d'inventaire utilisées (disponibilité, confidentialité, complexité, etc). Les données d'inventaire en ACV des produits de la mer sont de deux types :

- Des données primaires et spécifiques, décrivant les processus directement liés à la pêche et à l'aquaculture. Ces données sont généralement collectées par des enquêtes ou suivis de l'activité en question, ou bien par modélisation pour les données qui ne sont pas accessibles par enquêtes ou mesures. La qualité de ces données peut varier énormément entre les études.
- Des données secondaires et génériques décrivant les autres processus (transport, énergie, matériaux, etc) ayant lieu en dehors de l'activité de pêche et de l'aquaculture. Ces données sont généralement obtenues à partir des bases de données qui renseignent sur les consommations et émissions de produits de base. La qualité de ces bases est une des clés de la qualité d'une ACV. Par contre, il est nécessaire de tenir compte de la représentativité et de spécificité géographique et temporelle des données sélectionnées.

2.3. Variabilité et incertitude

Vu la nécessité en nombre et en qualité des données pour conduire une ACV, plusieurs lacunes sont généralement constatées dans les études ACV des systèmes de production de produits de la mer. Pour améliorer la précision de l'ACV, il est important de prendre en compte la variabilité entre les différents systèmes de production. Pour cela, il faut avoir des données sur un nombre suffisant de systèmes de production, soit en conduisant plusieurs enquêtes dans des systèmes différents ou bien en développant des stratégies d'échantillonnages spécifiques qui permettent de balayer cette variabilité. Hormis l'importante variabilité, la multitude de données nécessaire pour l'ACV génère aussi un niveau d'incertitude élevé. Même si plusieurs cadres méthodologiques existent pour l'intégration de l'incertitude dans l'ACV, leur utilisation nécessite un recul important sur les données ainsi qu'une expertise solide en mathématiques et en statistiques. L'incertitude dans l'ACV n'est pas seulement associée aux données primaires (provenant des enquêtes ou des modèles), mais aussi aux données secondaires issues des bases de données qui ne sont pas toujours adaptées aux contextes géographiques et temporels de l'étude. Dans les travaux de cette thèse, l'incertitude, ainsi que la variabilité entre fermes aquacoles et entre chalutiers de fond ont été prises en compte.

3. Perspectives d'amélioration

L'ACV des produits de la mer est en plein développement, avec un nombre croissant d'études ACV portant sur plusieurs systèmes de production différents. Les travaux présentés dans cette thèse ont montré que l'ACV permet de conduire une analyse environnementale pertinente de la production de produits de la mer par pêche au chalut de fond et par l'aquaculture. Dans ces travaux, il était aussi démontré que l'ACV permet de prendre en compte plusieurs aspects spécifiques à la pêche et à l'aquaculture pour proposer un bilan environnemental plus spécifique et adapté aux deux secteurs. Les ACV des systèmes de production des produits de la mer doivent continuer à mûrir et à consolider leurs bases méthodologiques. Mais les résultats obtenus de ce type d'analyse environnementale contribuent déjà à mettre en place des directives pour placer ces systèmes de production dans le contexte de développement durable. Malgré les progrès réalisés dans la conduite des ACV des produits de la mer, les marges d'amélioration restent importantes.

3.1. Extension du champ d'étude et des frontières des systèmes considérées

Parmi les aspects à améliorer, figure en particulier l'extension des frontières des systèmes de production étudiés pour intégrer les étapes post-production (pour l'aquaculture) et post-débarquement (pour le chalutage de fond). Ces étapes doivent inclure les étapes d'emballage, distribution, commercialisation, utilisation, et recyclage dans les analyses, puisque ces processus peuvent influencer les bilans environnementaux. Ceci permettra de passer d'une étude "du berceau à la porte" à une étude "du berceau à la tombe".

Les ACV menées dans ce travail étaient consacrées à l'évaluation des impacts environnementaux midpoints orientés problèmes seulement. Il pourrait donc être intéressant d'aller plus loin et étudier les impacts endpoints orientés dommages. Une autre perspective d'amélioration serait d'inclure les étapes facultatives de l'ACV. Par exemple : la normalisation des impacts environnementaux en calculant les impacts relatifs par rapport une référence (généralement une population humaine), la pondération des impacts pour mettre certains objectifs environnementaux en avant et l'agrégation qui permet de regrouper des indicateurs pour avoir une seule et unique note.

Il est aussi intéressant de prendre en compte la dimension spatiale et temporelle dans l'analyse environnementale dans les différentes étapes de l'ACV, vu la variabilité importante des performances environnementales des fermes aquacoles et des chalutiers de fond d'une année à l'autre et d'une région à l'autre. En effet, l'ACV ne prend pas en compte les spécificités régionales et locales des sites étudiés. Cet aspect est d'une importance capitale dans les ACV des produits de la mer, vu que les impacts de la pêche et de l'aquaculture varient selon le site d'implantation des fermes aquacoles et selon les zones d'opération des navires de pêche. Il sera également intéressant d'évaluer les performances environnementales d'autres pêcheries (pêche côtière, sennes, etc) et d'autres systèmes aquacoles en Tunisie (élevage dans des bassins à terre, engraissement de thon, etc), ceci peut fournir des informations importantes aux décideurs quant aux pêcheries et aux systèmes aquacole à encourager pour assurer la durabilité des deux secteurs.

3.2. Spécificités de la pêche et de l'aquaculture

Pour améliorer les études ACV des produits de la mer, il est important de mettre en place des valeurs seuils pour chaque type d'impact permettant d'émettre un jugement sur les niveaux des atteintes environnementales engendrées par la production des produits de la mer. Ces valeurs doivent être déterminées en prenant en compte les spécificités régionales de la pêche et de l'aquaculture et des caractéristiques des milieux aquatiques où ils opèrent.

Pour prendre en considération les spécificités des activités de la pêche et de l'aquaculture, il est également nécessaire d'intégrer les impacts biotiques qui en découlent. Quelques études ont proposé des cadres méthodologiques pour ajouter ces impacts à l'ACV pour mieux qualifier les impacts environnementaux des systèmes de production des produits de la mer et vérifier leur pertinence dans un contexte plus global (Langlois et al., 2015; Luong et al., 2015; Vázquez-Rowe et al., 2012c). En revanche, la plupart des indicateurs proposés (production primaire requise, impact sur les fonds marins, rejets, etc) ne sont pas compatibles aux critères de l'ACV et leurs calculs sont effectués en dehors de l'ACV. Étant donné que le but principal de l'ACV est de quantifier les impacts environnementaux d'une production, il est nécessaire que les impacts biotiques remplissent cette fonction et qu'ils ne soient pas simplement des indicateurs d'état des écosystèmes. Une autre difficulté d'intégration des impacts biotiques réside dans l'unité fonctionnelle ; en effet, les impacts environnementaux calculés par l'ACV sont tous rapportés à l'unité fonctionnelle choisie pour faciliter l'agrégation des catégories d'impacts et simplifier l'interprétation des résultats. Mais plusieurs indicateurs biotiques perdent leurs sens et leurs objectifs lorsqu'ils sont rapportés à l'unité fonctionnelle ; c'est le cas des indicateurs écologiques qui décrivent l'écosystème et les interactions entre ses composantes (par exemple le MTI, le niveau trophique des captures, etc). Il est donc nécessaire de mettre en place des catégories prenant en compte les impacts biotiques engendrés par la pêche et l'aquaculture qui soient compatibles et interprétables dans le cadre de l'ACV.

Pour mieux adapter les ACV conduites dans cette thèse au contexte géographique de la production des produits de la mer, il est nécessaire de mettre en place une catégorie d'impact prenant la biodiversité du milieu en considération. Cette catégorie doit permettre d'évaluer les effets des perturbations anthropiques sur les écosystèmes et leurs capacités de maintenir une communauté d'organismes équilibrée face aux modifications environnementales causées par la pêche et l'aquaculture. Il est également nécessaire d'évaluer les effets des échappements de poissons d'élevage dans le milieu naturel puisqu'ils peuvent avoir des conséquences sur différents niveaux (pollution génétique, concurrence trophique, dissémination de maladies et de parasites, etc.). De plus, il pourrait être intéressant de mettre en place une catégorie d'impact pour inclure les rejets de pêche dans le cadre de l'ACV, et le devenir des organismes une fois rejetés dans le milieu naturel.

3.3. Utilisation des biocarburants et substitution de la farine et de l'huile de poisson

L'ACV est une méthode multicritère qui permet une vision complète sur les conséquences environnementales possibles suite àn un changement ou une amélioration des pratiques de production. L'utilisation de l'huile et de la farine de poisson est largement débattue lorsque l'aquaculture est comparée la pêche (Ellingsen and Aanondsen, 2006). L'enjeu est de trouver d'autres sources de protéines tout en gardant les qualités nutritionnelles et organoleptiques des poissons d'aquaculture (Dias et al., 2009). Pour le secteur aquacole, plusieurs études ont montré que les aliments aquacoles contenant moins de farine et d'huile de poisson ont moins d'impact sur l'environnement (Middlemas et al., 2013). Bien que la substitution des farines et des huiles de poisson par des ingrédients d'origine agricole puisse avoir un effet positif sur le bilan environnemental global de l'aquaculture, il est important de bien évaluer les risques de transfert d'impacts suite à ce changement et de prendre en compte les aspects nutritionnels, économiques et environnementaux lors de la formulation de l'aliment pour poisson. La mise en place d'une ACV pour évaluer les impacts environnementaux après la substitution de la farine et de l'huile de poisson par d'autres ingrédients (farine et huile de tournesol, de soja, blé, maïs, etc) permettra de comprendre les transferts d'impacts possibles. Les transferts d'impacts peuvent avoir lieu entre catégorie d'impacts, entre processus et entre zones géographiques. Pour cela, il est important de prendre ces transferts en compte lors de la prise de décision concernant les ingrédients à utiliser pour la fabrication d'aliments pour poisson.

Les études environnementales de l'activité de la pêche ont montré qu'il est nécessaire de diminuer la consommation en carburant pour diminuer les impacts environnementaux du secteur (Avadí and Fréon, 2013b; Tyedmers, 2004). Le biocarburant est actuellement la seule source de carburant d'origine renouvelable directement utilisable. C'est un carburant produit à partir de matériaux organiques non fossiles. Il s'agit d'une source d'énergie alternative pour réduire les émissions de CO_2 et la dépendance aux comestibles fossiles, et ainsi limiter les émissions de CO_2 (Kumar, 2011). En revanche l'utilisation de biocarburant pour remplacer les énergies fossiles peut engendrer un transfert d'impacts vers d'autres processus et vers d'autres zones géographiques (Rajagopal et al., 2011). L'utilisation des biocarburants devrait avoir des effets environnementaux positifs dans les pays les utilisant, mais un fort impact environnemental dans les pays les produisant. De plus, il y a d'autres émissions atmosphériques qui résultent de la combustion et la production des biocarburants (Al-Riffai et al., 2010; Sánchez-Arreola et al., n.d.). Il est pourrait être intéressant d'utiliser l'ACV pour évaluer les impacts environnementaux de l'utilisation des biocarburants et ensuite comparer les résultats avec le cas des carburants d'origine fossile. Il est également important de prendre en compte les aspects économiques et sociaux lors de l'analyse environnementale de l'utilisation du biocarburant.

3.4. Toxicité

Le déversement des substances chimiques (par agriculture, aquaculture, pêche, etc) dans le milieu naturel peut avoir un impact toxique immédiat (toxicité aiguë) ou différé (toxicité par bioaccumulation ou bioamplification). Le potentiel toxique des substances chimiques dépend de la quantité déversée. Même si les substances toxiques sont généralement présentes dans le milieu marin à l'état de traces, elles peuvent se concentrer en parcourant la chaine trophique et finir par contaminer certaines populations (Middlemas et al., 2013). La pêche et l'aquaculture sont responsables de l'émission de quantités importantes de substances chimiques dans le milieu naturel. Pour la pêche, les émissions des substances chimiques sont liées à l'utilisation de la peinture et de la peinture antifouling. Dans le cas de l'aquaculture, l'émission de ces substances est principalement liée à l'utilisation des antibiotiques et des médicaments vétérinaires.

Dans le cadre de l'ACV, il existe des catégories d'impacts traitant le potentiel toxique engendré par la production. Il est important de prendre le cadre géographique et les caractéristiques des milieux où les substances sont déversées dans cette catégorie d'impact. En effet, les substances chimiques déversées dans le milieu marin peuvent être détruites ou transformées par plusieurs actions (hydrolyse, oxydation, etc.) selon le milieu. En revanche, il y a plusieurs substances persistantes et non dégradables (zinc, cadmium, plomb, etc) qui ont un impact toxique plus élevé.

3.5. ACV et modélisation

Une autre perspective à envisager est le couplage des ACV avec des modèles d'analyse énergétiques, puisque les ACV ne prennent pas en considération les flux d'énergie d'origine naturelle (énergie solaire, énergie éolienne, etc) ni leurs qualités. Il est donc intéressant d'associer les ACV à des méthodes comme l'émergie (Wilfart et al., 2013) et l'exergie (Portha et al., 2010). L'émergie est une méthode qui permet de transformer les flux d'énergie incorporés dans une production en équivalent d'énergie solaire. L'exergie permet de mesurer la qualité de l'énergie, il s'agit de la partie utilisable d'un joule d'énergie. L'utilisation de ces méthodes permet de comprendre l'origine et la qualité des flux d'énergies et leur dépendance aux ressources naturelles. Les ACV et les modèles d'analyses énergétiques sont complémentaires, la première se focalise sur les impacts anthropiques et la deuxième sur l'influence des ressources énergétiques naturelles.

Dans cette thèse, des approches de modélisation ont été combinées avec l'ACV de la pêche et de l'aquaculture. Comme toutes approches de modélisation, les limitations dues aux hypothèses sous-jacentes de chaque modèle et les approximations effectuées pour des besoins du calcul et pour combler l'insuffisance de données font que ces modèles soient des simplifications de la réalité. L'ACV de la pêche a été complétée par des indicateurs issus du modèle écosystémique EwE avec son module spatialisé Ecospace. La contrainte principale du modèle EwE réside dans les hypothèses de base du modèle, dans les choix de paramétrisation et l'importante incertitude des données d'entrée. La limite majeure du modèle est la disponibilité des données spatialisées ainsi que la simplification des mouvements des espèces dans l'écosystème, qui sont basés simplement sur les types d'habitats et qui négligent totalement les phénomènes migratoires. Ces modèles peuvent être améliorés si plus de données actualisées sont disponibles vu l'énorme incertitude des paramètres inclus dans le modèle. Pour l'ACV de l'aquaculture, un modèle MERAMOD été développé pour quantifier l'impact de l'élevage sur les fond marins. La précision des prédictions de ce modèle peut être renforcée en prenant en considération la remise en suspension de matières organiques déposées sur les fonds marins en incluant différents niveaux de circulation des courants d'eau sous les cages d'aquaculture. Mais ceci dépend aussi de la disponibilité des données spécifiques.

3.6. ACV et les objectifs du développement durable

Les ACV traditionnelles ont pour objectif principal de quantifier les impacts et les atteintes environnementales, et ne répondent donc qu'au pilier environnemental du développement durable. Il est important d'intégrer les deux autres piliers (social et économique) pour pouvoir définir et proposer des mesures de gestion en adéquation avec les objectifs du développement durable. En effet, l'ACV ouvre de nouvelles perspectives pour placer les systèmes de produits de la mer dans un cadre de durabilité, mais il est indispensable de considérer la complexité de la dimension socio-économique de la pêche et de l'aquaculture pour mieux concilier les enjeux écologiques, économiques et sociaux.

Une perspective d'amélioration des études ACV des produits de la mer est de mettre en œuvre une nouvelle catégorie d'impact multicritère, permettant à la fois de quantifier les impacts environnementaux et les effets positifs des deux activités. En plus de l'impact sur l'environnement, cette catégorie doit tenir compte des rôles de la pêche et de l'aquaculture dans la fourniture de services socio-économiques ainsi que la fourniture des ressources protéiques. Ce qui permet de passer d'une simple évaluation environnementale à une évaluation d'efficacité socio-économique et écologique des systèmes de production. Pour cela, il faut se baser sur les trois critères d'évaluation principaux : (i) l'évaluation du potentiel des systèmes de production étudiés, (ii) l'évaluation de la valeur globale en services non marchands offerts par l'activité de la pêche et de l'aquaculture, et (iii) l'évaluation des effets de ces activités sur l'environnement. En conclusion, cette approche permettrait d'acquérir des informations importantes sur l'efficacité écologique et socio-économique des systèmes de production de produits de la mer pour pouvoir développer des systèmes de production raisonnées dans le contexte de développement durable.

Parmi les aspects sociaux durables (people) à prendre en compte pour compléter les évaluations environnementales, il est important de considérer les conditions de travail qui doivent respecter les normes de sécurité et d'hygiène et être respectueuses des travailleurs et des utilisateurs et de leur santé lors de la production et l'utilisation des produits de la mer. Il est également important de considérer le bien-être des employés et des clients. Pour le pilier économique (profit), il est important que les produits de la mer génèrent des bénéfices afin que la production soit rentable et qu'elle permet de créer des emplois de qualité avec des travailleurs suffisamment rémunérés. Il est également indispensable de prendre en compte le renforcement de l'économie locale et les emplois indirects liés à la production de produits de la mer (fournisseur de matériaux primaires, service d'entretien et de maintenance, etc). Il est également intéressant d'utiliser des valeurs monétaires comme unité fonctionnelle lors de l'évaluation environnementale des produits de la mer, ce qui permettra de conduire une analyse plus complète en associant les aspects environnementaux, économiques et sociaux. Mais le problème de ce genre d'approche est le fait que les paramètres économiques varient beaucoup selon le contexte socio-économique puisque la valeur donnée à un produit ou un service changent selon les cultures, les habitudes et la société.

Le cadre méthodologique de l'ACV se focalise uniquement sur le pilier environnemental qui est la première dimension du développement durable. Néanmoins, les deux autres piliers ne sont pas intégrés et par conséquent, il est important que les décisions prises à la lumière des ACV se font en conduisant des analyses économiques et sociales complémentaires.

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Les annexes

Appendix 2.1 : Ingredients and chemical composition of fish feed used on aquaculture farms in Tunisia (the brand name is confidential).

	Fish feed	Origin
Ingredients ($g\ kg^{-1}$)		
Fish meal	380	Peru
Fish oil	280	Peru
Soybean meal	150	Brazil
Grain maize meal	50	France
Wheat	35	France
Wheat gluten meal	35	France
Sunflower meal	10	France
Pea meal	35	France
Rapeseed meal	10	France
Vitamin and mineral premix	15	
Chemical composition (%)		
Crude protein	46	
Crude fat	16	
Crude fibre	3.5	
Ash	6.5	
Phosphorus	0.9	
Sodium	0.2	
Calcium	0.8	
Gross energy ($MJ\ kg^{-1}$)	16.1	

Appendix 2.2 : Names of unit processes (some from ecoinvent 3.0) used to model fish production. Detailed life cycle inventories and quantities could not be provided due to the confidential nature of this information.

Fish production (seabream or seabass)

Materials

1. Fish feed (for seabream or seabass)

Materials

Fish meal and oil South America, with wastewater treatment, Peru PE U (biomass allocation)

Resources: Water, cooling, salt, ocean

Materials:

- Anchovy landed for fish oil and fish meal, South America, Peru PE U
- Tap water {Europe without Switzerland}| market for | Alloc Def, U
- Electricity, low voltage {BR}| market for | Alloc Def, U
- Heat, central or small-scale, other than natural gas {Europe without Switzerland}| heat production, light fuel oil, at boiler 100kW, non-modulating | Alloc Def, U
- Sodium hydroxide, without water, in 50% solution state {GLO}| market for | Alloc Def, U
- Formaldehyde {GLO}| market for | Alloc Def, U
- Methanol {GLO}| market for | Alloc Def, U
- Sulfuric acid {GLO}| market for | Alloc Def, U
- Nitric acid, without water, in 50% solution state {GLO}| market for | Alloc Def, U
- Hydrochloric acid, without water, in 30% solution state {RER}| market for | Alloc Def, U

Emissions to air: Heat, waste

Waste to treatment: Wastewater from potato starch production {GLO}| market for | Alloc Def, U

Soybean meal common process BR U

Grain maize Conv. FR U

Wheat starch, at plant, with water treatment, FR

Wheat gluten, at plant, with water treatment, FR

Sunflower meal FR U

Protein Pea Conv. Fert. chem. FR U

Rape seed FR U

Vitamin and mineral premix, France FR
Packaging film, LDPE, from plant production to fish feed plant, France FR U

Electricity/heat

Electricity, medium voltage {IT}| market for | Alloc Def, U
Heat, central or small-scale, natural gas {Europe without Switzerland}| market for heat, central or small-scale, natural gas | Alloc Def, U
Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U
Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U

2. Fingerlings(seabream or seabass)

Resources:

- Water, salt, ocean
- Land use II-III

Materials

- Hatchery total Feed
- Hatchery facilities
- Hatchery Total Equipment
- Chlorine, gaseous {RER}| market for | Alloc Def, U

Electricity/heat

- Electricity Greece B250
- Liquid Oxygen
- Transport, freight, lorry 28 metric ton, vegetable oil methyl ester 100% {GLO}| market for | Alloc Def, U
- Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U

Emissions to water

- Nitrogen, total, dissolved
- Phosphorus, total, solid
- ThOD (Theoretical oxygen demand)

3. Equipment

Sea cages
Boats

Buoys and anchors
Zodiac boat
4. Building, hall {GLO}| market for | Alloc Def, U

Electricity/heat

Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U
Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U
Heat, central or small-scale, other than natural gas {RoW}| heat production, light fuel oil, at boiler 10kW, non-modulating | Alloc Def, U

Emissions to water

Phosphorus, total, dissolved
Phosphorus, total, solid
Nitrogen, total, dissolved
Nitrogen, total, solid
ThOD (Theoretical oxygen demand)

Appendix 2.3 : Input data used in grid-generation and particle-tracking modules of the MERAMOD® model

Input	Value
Total grid size (m)	285 × 285
Grid cell resolution (m)	3 × 3
Number of cages	36
Shape of cages	circular
Diameter of cages (m)	22 and 29
Depth under the cages (m)	32
Current velocity ($cm.s^{-1}$)	10.5
Food water content (%)	9
Food digestibility (%)	70
Food wastage (%)	5
Dispersion coefficients ($m.s^{-1}$)	0.1; 0.1; 0.001
Food-settling velocity ($cm.s^{-1}$)	9.5
Fecal settling velocity ($cm.s^{-1}$)	3.5
Trajectory-evaluation accuracy (s)	60

Appendix 3.1 : Names of unit processes (from ecoinvent 3.0) used to model seafood production by demersal trawling in the Gulf of Gabes. Detailed Life Cycle Inventory and quantities could not be provided due to confidentiality.

Seafood production by demersal trawling

Materials

1. Construction of trawling vessel

Materials

Engine

- Cast iron {GLO}| market for | Alloc Def, U
- Steel, chromium steel 18/8 {GLO}| market for | Alloc Def, U
- Aluminium alloy, AlMg3 {GLO}| market for | Alloc Def, U

Sawnwood, azobe from sustainable forest management, planed, air dried {GLO}| market for | Alloc Def, U

Steel, low-alloyed {GLO}| market for | Alloc Def, U

Copper {GLO}| market for | Alloc Def, U

Aluminium alloy, AlMg3 {GLO}| market for | Alloc Def, U

Electricity/heat

Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U

Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U

2. Construction of trawling net

Materials

- Polyethylene, high density, granulate {GLO}| market for | Alloc Def, U
- Nylon 6-6 {GLO}| market for | Alloc Def, U
- Lead {GLO}| market for | Alloc Def, U
- Steel, chromium steel 18/8 {GLO}| market for | Alloc Def, U

Electricity/heat

- Transport, freight, lorry 28 metric ton, vegetable oil methyl ester 100% {GLO}| market for | Alloc Def, U
- Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U

3. Antifouling paint

Zinc oxide {GLO}| market for | Alloc Def, U
Copper oxide {GLO}| market for | Alloc Def, U
Xylene {GLO}| market for | Alloc Def, U
Solvent, organic {GLO}| market for | Alloc Def, U

4. Paint for trawler
5. Diesel, low-sulfur {RoW}| market for | Alloc Def, U
6. Lubricating oil {GLO}| market for | Alloc Def, U

Electricity/heat

Transport, freight, sea, transoceanic ship {GLO}| market for | Alloc Def, U
Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U
Heat, central or small-scale, other than natural gas {RoW}| heat production, light fuel oil, at boiler 10kW, non-modulating | Alloc Def, U

Emissions to air

Carbon monoxide
Sulfur dioxide
Carbon dioxide
Volatile organic compounds
Nitrogen oxides

Emissions to water

Xylene
Copper oxide
Zinc compounds

Appendix 3.2 : Significance test (p-value) between the four groups of demersal trawling vessels according to impact category. G1: low impact, G2: medium impact, G3: high impact, G4: very high impact. ADP= Abiotic Depletion Potential, AP= Acidification Potential, EP= Eutrophication Potential, GWP= Global Warming Potential, ODP= Ozone Depletion Potential, POFP= Photochemical Oxidant Formation Potential, HTP= Human Toxicity Potential, METP= Marine Eco-Toxicity Potential, TETP= Terrestrial Eco-Toxicity Potential, LOP= Land Occupation Potential, TCED= Total Cumulative Energy Demand.

	ADP-G1	**ADP-G2**	**ADP-G3**
ADP-G2	$3.58e^{-12}$		
ADP-G3	$1.85e^{-10}$	$6.86e^{-08}$	
ADP-G4	0.0001	0.0002	0.0017

	LOP-G1	**LOP-G2**	**LOP-G3**
LOP-G2	$4.09e^{-11}$		
LOP-G3	$1.95e^{-09}$	$4.80e^{-07}$	
LOP-G4	$1.21e^{-05}$	$3.49e^{-05}$	0.0002

	EP-G1	**EP-G2**	**EP-G3**
EP-G2	$3.83e^{-12}$		
EP-G3	$1.74e^{-10}$	$5.81e^{-08}$	
EP-G4	$9.60e^{-05}$	0.0002	0.0016

	METP-G1	**METP-G2**	**METP-G3**
METP-G2	$2.56e^{-11}$		
METP-G3	$1.28e^{-09}$	$3.29e^{-07}$	
METP-G4	$9.13e^{-06}$	$2.64e^{-05}$	0.0002

	AP-G1	**AP-G2**	**AP-G3**
AP-G2	$3.47e^{-12}$		
AP-G3	$1.94e^{-10}$	$7.45e^{-08}$	
AP-G4	$1.61e^{-05}$	$5.21e^{-05}$	0.0004

	ODP-G1	**ODP-G2**	**ODP-G3**
ODP-G2	$1.55e^{-13}$		
ODP-G3	$1.30e^{-10}$	$7.09e^{-08}$	
ODP-G4	0.0001	0.0003	0.0017

	GWP-G1	**GWP-G2**	**GWP-G3**
GWP-G2	$3.57e^{-12}$		
GWP-G3	$1.87e^{-10}$	$6.96e^{-08}$	
GWP-G4	$1.57e^{-05}$	$5.05e^{-05}$	0.0004

	POFP1	**POFP-G2**	**POFP-G3**
POFP-G2	$1.04e^{-11}$		
POFP-G3	$1.34e^{-08}$	$5.22e^{-07}$	
POFP-G4	$1.62e^{-05}$	$8.23e^{-05}$	$3.49e^{-04}$

	HTP-G1	**HTP-G2**	**HTP-G3**
HTP-G2	$1.39e^{-10}$		
HTP-G3	$4.95e^{-09}$	$1.14e^{-06}$	
HTP-G4	$5.60e^{-06}$	$1.49e^{-05}$	$9.75e^{-05}$

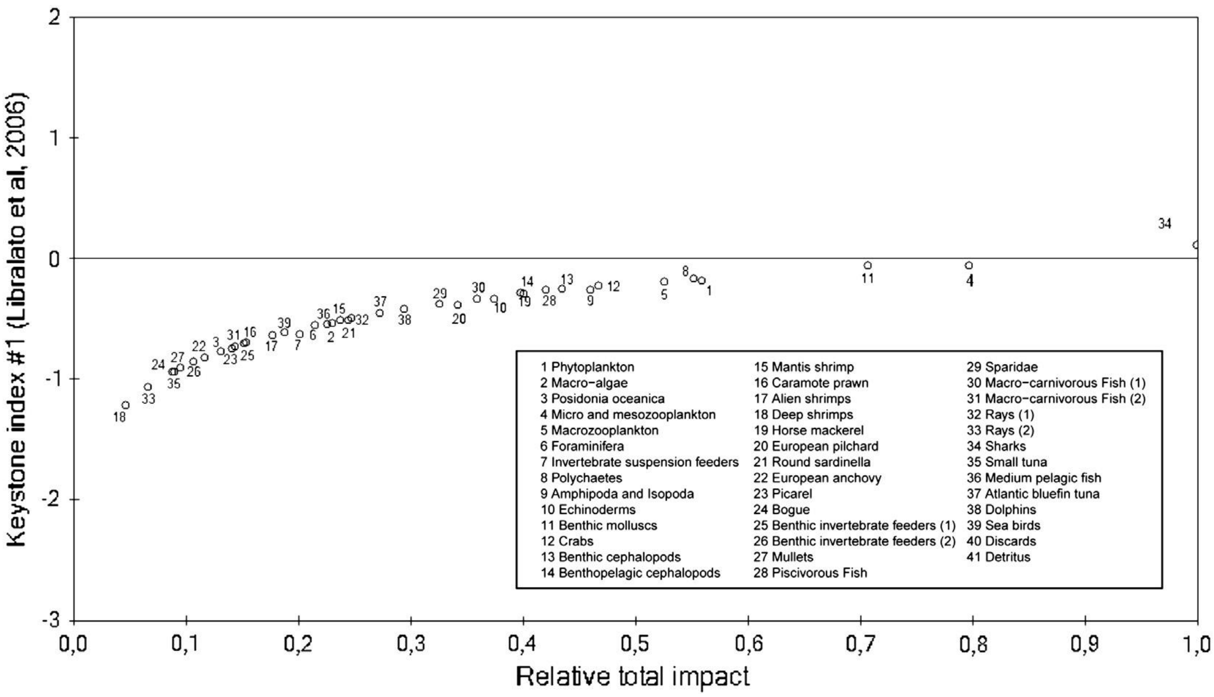
	TETP1	**TETP3**	**TETP4**
TETP3	$1.04e^{-09}$		
TETP4	$2.32e^{-08}$	$4.58e^{-06}$	
TETP5	$3.48e^{-06}$	$8.17e^{-06}$	$4.19e^{-05}$

	TCED-G1	**TCED-G2**	**TCED-G3**
TCED-G2	$3.58e^{-12}$		
TCED-G3	$1.85e^{-10}$	$6.87e^{-08}$	
TCED-G4	$1.57e^{-05}$	$5.05e^{-05}$	0.0004

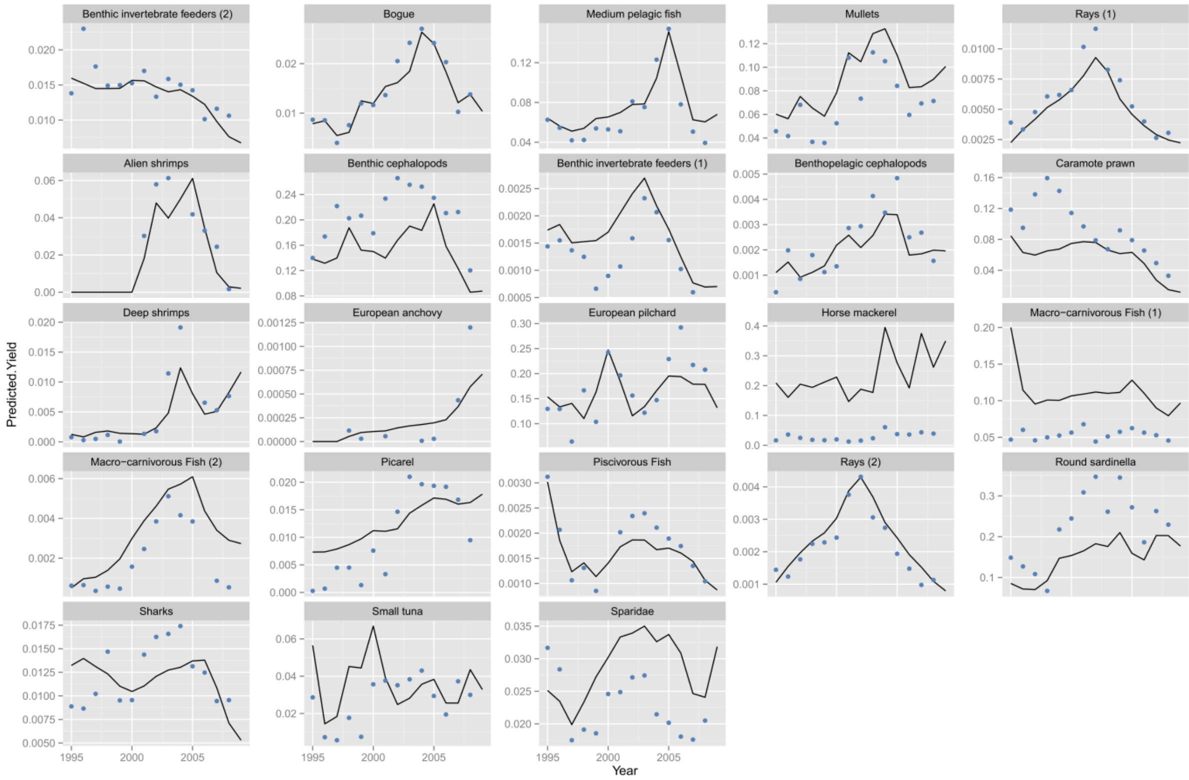
Appendix 3.3 : Parameters of the Ecopath model of the Gulf of Gabes ecosystem (Hattab et al., 2013)

Functional group	Trophic level	Biomass ($t.km^{-2}$)	Production / biomass ($.year^{-1}$)	Consumption / biomass ($.year^{-1}$)	Ecotrophic efficiency	Production / consumption
Phytoplankton	1.000	7.650	160.000	0.000	0.309	
Macro-algae	1.000	2.188	13.400	0.000	0.950	
Posidonia oceanica	1.000	0.046	15.033	0.000	0.950	
Micro and mesozooplankton	2.105	8.460	32.395	51.069	0.950	0.634
Macrozooplankton	3.093	3.463	22.650	56.570	0.950	0.400
Foraminifera	2.000	0.368	7.844	23.532	0.950	0.333
Invertebrate suspension feeders	2.725	7.382	1.647	9.904	0.950	0.166
Polychaetes	2.361	4.416	3.502	19.723	0.950	0.178
Amphipoda and Isopoda	2.000	5.464	2.405	26.199	0.950	0.092
Echinoderms	2.327	4.526	0.570	2.460	0.950	0.232
Benthic molluss	2.353	4.258	1.886	9.386	0.950	0.201
Crabs	3.211	2.089	2.555	4.953	0.950	0.516
Benthic cephalopods	3.701	0.552	2.800	5.642	0.968	0.496
Benthopelagic cephalopods	4.225	0.065	2.712	31.640	0.885	0.086
Mantis shrimp	3.716	0.560	1.590	4.854	0.884	0.328
Caramote prawn	3.279	0.131	2.260	7.665	0.994	0.295
Alien shrimp	2.868	0.125	3.800	7.665	0.996	0.496
Deep shrimp	3.270	0.036	2.796	7.665	0.952	0.365
Horse mackerel	3.663	1.550	0.716	9.044	0.997	0.079
European pilchard	3.122	3.829	1.116	11.403	0.927	0.098
Round sardinella	3.125	1.850	0.853	9.635	0.953	0.089
European anchovy	3.081	0.700	1.089	10.505	0.882	0.104
Picarel	3.104	0.618	0.882	27.280	0.791	0.032
Bogue	3.200	0.538	0.772	19.813	0.782	0.039
Benthic invertebrate feeders (1)	3.537	0.210	0.608	6.834	0.997	0.089
Benthic invertebrate feeders (2)	3.391	0.049	0.723	8.529	0.946	0.085
Mullets	3.305	0.085	1.310	6.587	0.990	0.199
Piscivorous fish	4.213	0.067	0.359	4.335	0.788	0.083
Sparidae	3.313	0.216	0.779	7.832	0.959	0.099
Macro-carnivorous fish (1)	4.026	0.189	0.639	9.380	0.999	0.068
Macro-carnivorous fish (2)	4.056	0.052	0.571	8.529	0.949	0.067
Rays (1)	4.060	0.363	0.239	3.277	0.095	0.073
Rays (2)	3.780	0.133	0.342	3.736	0.267	0.092
Sharks	4.355	0.193	0.544	4.233	0.220	0.128
Small tuna	4.419	0.074	0.591	8.193	0.950	0.072
Medium pelagic fish	4.118	1.462	0.111	1.306	0.891	0.085
Atlantic bluefin tuna	4.381	0.230	0.313	3.513	0.899	0.089
Dolphins	4.339	0.080	0.075	14.361	0.000	0.005
Sea birds	3.772	0.002	0.200	62.751	0.000	0.003

Discards	1.000	0.381	0.447
Detritus	1.000	30.000	0.280



Appendix 3.4 : The keystone index and the relative total impact of each functional group in the model (Hattab et al., 2013).



Appendix 3.5 : Comparison of the time series of landings (points) and model outputs (lines) for the period 1995-2008

Appendix 3.6 : Input parameters applied to each group in the Gulf of Gabes Ecospace model (Abdou et al., 2016).

Functional group	Trophic level	Base dispersal rate (km year^{-1})	Relative dispersal rate in bad habitat	Relative vulnerability to predation in bad habitat	Relative feeding rate in bad habitat
Phytoplankton	1.00	3	1	2	0.95
Macro-algae	1.00	3	1	2	0.95
Posidonia oceanica	1.00	3	1	2	0.95
Micro and mesozooplankton	2.10	3	1	2	0.01
Macrozooplankton	3.09	3	1	2	0.01
Foraminifera	2.00	3	1	2	0.01
Invertebrate suspension feeders	2.72	3	1	2	0.01
Polychaetes	2.36	3	1	2	0.01
Amphipoda and Isopoda	2.00	3	1	2	0.01
Echinoderms	2.32	3	1	2	0.01
Benthic mollusks	2.35	3	2	2	0.01
Crabs	3.21	3	2	2	0.01
Benthic cephalopods	3.70	3	2	2	0.30
Benthopelagic cephalopods	4.22	3	2	2	0.60
Mantis shrimp	3.71	30	2	2	0.30
Caramote prawn	3.27	30	2	2	0.01
Alien shrimp	2.86	30	2	2	0.01
Deep shrimp	3.27	30	2	2	0.01
Horse mackerel	3.71	300	3	2	0.30
European pilchard	3.12	300	3	2	0.01
Round sardinella	3.12	300	3	2	0.01
European anchovy	3.08	300	3	2	0.01
Picarel	3.10	300	3	2	0.01
Bogue	3.20	300	3	2	0.01
Benthic invertebrate feeders (1)	3.53	300	3	2	0.30
Benthic invertebrate feeders (2)	3.39	300	3	2	0.01
Mullets	3.30	300	2	2	0.01
Piscivorous fish	4.21	300	3	2	0.60
Sparidae	3.35	300	4	2	0.01
Macro-carnivorous fish (1)	4.02	300	4	2	0.60
Macro-carnivorous fish (2)	4.05	300	4	2	0.60
Rays (1)	4.06	30	4	2	0.60
Rays (2)	3.78	30	4	2	0.30
Sharks	4.35	300	5	2	0.60
Small tuna	4.45	300	5	2	0.60
Medium pelagic fish	4.12	300	5	2	0.60
Atlantic bluefin tuna	4.43	300	5	2	0.60
Dolphins	4.34	300	5	2	0.60
Sea birds	3.77	300	5	2	0.30

Appendix 3.7 : Preferred habitat of functional groups in the model. (+) sign indicates the habitat assigned to a specific functional group (Abdou et al., 2016)

Functional group	Habitat type									
	All	Deep mud	Offshore muddy sand and gravel	Circalittoral bioclastic muddy sand				*Posidonia* high density	*Posidonia* medium density	*Posidonia* low density
Depth range (m)		>100	>100	>100	50-100	35-50	20-35	20-35	35-50	20-35
Phytoplankton	+									
Macro-algae						+	+	+	+	+
Posidonia oceanica								+	+	+
Micro and mesozooplankton	+									
Macrozooplankton	+									
Foraminifera	+									
Invertebrate suspension feeders	+									
Polychaetes	+									
Amphipoda and Isopoda	+									
Echinoderms	+									
Benthic mollusks	+									
Crabs	+									
Benthic cephalopods	+									
Benthopelagic cephalopods	+									
Mantis shrimp					+	+	+	+	+	+
Caramote prawn					+	+	+	+	+	+
Alien shrimp					+	+	+	+	+	+
Deep shrimp		+	+	+	+					
Horse mackerel	+									
European pilchard	+									
Round sardinella	+									
European anchovy	+									
Picarel	+									
Bogue	+									
Benthic invertebrate feeders (1)	+									
Benthic invertebrate feeders (2)	+									
Mullets	+									
Piscivorous fish	+									
Sparidae					+	+	+	+	+	+
Macro-carnivorous fish (1)	+									
Macro-carnivorous fish (2)	+									
Rays (+)	+									
Rays (2)	+									
Sharks	+									
Small tuna	+									
Medium pelagic fish	+									
Atlantic bluefin tuna	+									
Dolphins	+									
Sea birds	+									

Appendix 3.8 : Distribution of fleets among habitat types. (+) sign indicates fishable habitat per fleet (Abdou et al., 2016)

Fleet	Habitat type								
	Deep mud	Offshore muddy sand and gravel	Circalittoral bioclastic muddy sand				*Posidonia* high density	*Posidonia* medium density	*Posidonia* low density
Depth range (m)	>100	>100	20-35	35-50	50-100	>100	20-35	35-50	20-35
Coastal fishing			+	+	+		+	+	+
Fishing with lights fishing	+	+		+	+	+		+	
Small seine	+	+	+	+	+	+	+	+	+
Tuna purse seine	+	+		+	+	+		+	
Demersal trawling	+	+			+	+			
Sponge fishing			+				+		+

Appendix 3.9 : Exploring the potential effects of marine protected areas on the ecosystem structure of the Gulf of Gabes using the Ecospace model

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Exploring the potential effects of marine protected areas on the ecosystem structure of the Gulf of Gabes using the Ecospace model

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Abstract – The Gulf of Gabes is considered as one of the most productive areas of the southern Mediterranean Sea and it plays an important role in Tunisian economy. It is known to be an archetypal ecosystem in which the effects of fisheries are the most pronounced. Based on the stock assessment outcomes, it is as a highly exploited ecosystem. Thereupon, it becomes necessary to establish adequate measures to facilitate the recovery of the marine resources. The most important sets of management measures regard the establishment of Marine Protected Areas (MPAs). However, these management plans should be assessed beforehand to make sure of the relevance of the measure and its impact on marine resources. Modeling may significantly enhance our understanding of the likely impacts of fisheries management plans on groups that are very difficult to study and this approach gives insights at larger spatial scales. We used Ecospace to investigate the potential impacts of several spatial management plans on the ecosystem structure of the Gulf of Gabes. The Ecospace model is based on the existing Ecopath model elaborated by Hattab (2013). The simulation were carried over a 15-year period. The outcomes of the simulations, suggest that the implementation of MPAs in the Gulf of Gabes could be simultaneously beneficial for the ecosystem and fishing activities. However, the benefits are related to the characteristics of the MPA. The spatial simulations highlight that the location is crucial to the success of the MPA. Additionally, an increase in the size of a MPA can result in an increase in the spillover effect and, consequently, in catches in the neighborhood without harming ecosystem integrity. The configuration of the implemented MPA is of capital importance, a set of many small MPAs is more beneficial than fewer and larger MPAs, especially in terms of catches.

Keywords: Ecospace / Gulf of Gabes / fisheries management / marine protected areas (MPA)

1 Introduction

The demand for seafood has increased rapidly since the Industrial Revolution with the increase in human population size, resulting in substantial expansion of fisheries (Jackson et al. 2001; Halpern et al. 2008). Fishing activities not only expanded in terms of number of fishing units but also in terms of fishing grounds, including waters of all depths and habitat types (Pauly et al. 2002). The increased provision of seafood entails risks of ecological deterioration of marine ecosystems, as well as direct and indirect impacts of fisheries on the ecosystem (Jennings and Kaiser 1998; Kaiser and de Groot 2000). In addition to depleting target stocks and changing species abundance (Lotze et al. 2006), fishing may modify food webs and destroy habitats (Pauly et al. 2002; Worm et al. 2006). Furthermore, Mediterranean marine ecosystems are subject to several other anthropogenic pressures, such as habitat degradation, pollution, climate change and invasion by exotic species (Coll et al. 2010).

The focus of traditional fisheries management has been on single species, which does not account for the temporal and biological complexity and dynamics of ecosystems. Therefore, a shift towards integrated and more comprehensive approaches to management has become a necessity to manage the increase in resource use and to maintain the structure and functioning

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of ecosystems (Browman and Stergiou 2004). This shift is currently underway via ecosystem-based management approaches and the use of marine spatial planning tools that aim to exploit marine resources in a sustainable and profitable manner while maintaining a balanced ecosystem (Cochrane and De Young 2008).

The designation of marine protected areas (MPA) is a widely advocated approach to marine resource management (Colléter et al. 2014; Gell and Roberts 2003; Lubchenco et al. 2003), and protected areas have been implemented worldwide as part of the ecosystem-based approach (Gaines et al. 2010; Pauly et al. 2002). MPAs have proven to be effective for the protection of marine biodiversity, minimizing the negative impact of human activities (Gaines et al. 2010; Rossetto et al. 2015). In addition to the benefits inside an MPA, which allow the abundance and biodiversity of some fish populations to increase, an MPA may be beneficial for the surrounding fishing zones through the emigration of fishes and the export of pelagic eggs and larvae, which can sustain recruitment in those adjacent areas (Gell and Roberts 2003; Gerber et al. 2003; Harrison et al. 2012). The increase of catches around an MPA may be explained by a "spillover" effect, characterized by the export of fish and reproductive propagules to adjacent unprotected areas after increasing their densities and sizes inside the MPA (Gell and Roberts 2003; Ward et al. 2001).

MPAs can also have unexpected negative effects. For example, when an MPA favors the increase of predators, a decrease in prey populations might occur. This phenomenon has been identified in several ecosystems (e.g., Malindi Kisite and Watamu Marine National Parks in Kenya; Leigh Marine Reserve in New Zealand; and Brackett's Landing Conservation Area in the USA; Pinnegar et al. 2004). Moreover, the establishment of an MPA could result in a decrease in catches, especially in the short term (Colléter et al. 2014). In some cases an MPA is considered a biological success but a social failure (e.g., Bunaken National Park in Indonesia; San Salvador Island, Twin Rocks, Balicasag Island, Glan Padidu Marine Sanctuary and Kapatan Marine Reserve in the Philippines) (Christie 2004; Razon et al. 2012). Therefore, it is important to evaluate the potential effects of an MPA beforehand. Its expected effectiveness is directly related to location, size and configuration (Browman and Stergiou 2004; Halpern 2003; Hilborn et al. 2004).

Ecosystem models can be used to assess potential ecosystem responses to multiple management scenarios (Christensen et al. 2008; Coll and Libralato 2012). Among the available ecosystem models, Ecopath with Ecosim (EwE, Christensen and Walters 2004) is one of the most widely used. The Ecospace module (Walters et al. 1999) of EwE allows for assessment of the effectiveness of multiple potential marine protected areas as it considers the dispersal rates of species as well as the spatial distribution of fishing efforts. The Ecospace framework has been used in several studies (Fouzai et al. 2012; Romagnoni et al. 2015). To the best of our knowledge, this study represents the first attempt to use this method to assess fishery management alternatives in the Southern Mediterranean Sea.

The Gulf of Gabes is a major fishing ground off Tunisia of great economic and ecological importance, and is considered to be one of the most productive areas in the Mediterranean Sea in terms of catches (Papaconstantinou and Farrugio 2000). However, since the 1980s, there has been an expansion of fisheries and, as a result, several stocks such as hake have been reported to be highly or over-exploited (Fiorentino et al. 2008). Based on Fisheries and Aquaculture Department (DGPA) statistics, a continual increase in the number of trawlers occurred from early 1980 until 1991 (285 trawlers) followed by a decline to 229 trawlers in 1997. Since 1997, the number of trawlers has fluctuated around 250. The increase in the fleet size can be explained by the richness of benthic resources (shrimps, mullets, soles, etc.) and the presence of soft bottom habitats facilitating access to these resources (Missaoui et al. 2000).

Therefore, a mass-balance model has been developed to further understand the functioning of the ecosystem and to represent the average situation of the Gulf (Hattab et al. 2013a). Based on this model, we developed an Ecospace model to assess potential ecosystem feedbacks for several spatial management scenarios (marine protected areas).

2 Materials and methods

2.1 Study area

The Gulf of Gabes is located in the southern Mediterranean Sea on the eastern coast of Tunisia, and covers approximately 35 900 km^2 (Fig. 1). An important feature of this region is the unique geomorphological and hydrodynamic pattern. The basin is very shallow (a depth of 200 m is only reached at a distance of 400 km from the coastline), which increases the sensitivity to atmospheric changes (Natale et al. 2006). The Gulf is also known to have the highest tidal amplitude in the Mediterranean, reaching 1.8 m in height (Sammari et al. 2006).

The Gulf of Gabes is home to one of the world's largest seagrass beds of *Posidonia oceanica* (Batisse and Jeudy de Grissac 1998), offering a nursery ground for many marine species (Hattour 1991). The seafloor is primarily soft bottom (Brahim et al. 2003), resulting in the prevalence of bottom trawling activities in these waters.

2.2 Ecopath with Ecosim model of the Gulf of Gabes

Ecopath, in essence, represents a static snapshot of interactions between functional groups in an ecosystem (Christensen and Walters 2004). Ecopath is a mass-balance model based on the master equation (1):

$$P_i = Y_i + B_i M2_i + E_i + BA_i + P_i\,(1 - EE_i) \qquad (1)$$

where P_i is the production of functional group i, Y_i the fishery catch rate, B_i the biomass of group i, $M2_i$ represents predation mortality, E_i the net migration rate (emigration – immigration), BA_i the biomass accumulation rate, $P_i(1 - EE_i)$ the mortality from other sources and EE_i represents ecotrophic efficiency.

Equation (1) describes how to split the production of each group into components. Ecopath further splits the internal energy flow for each group according to the following

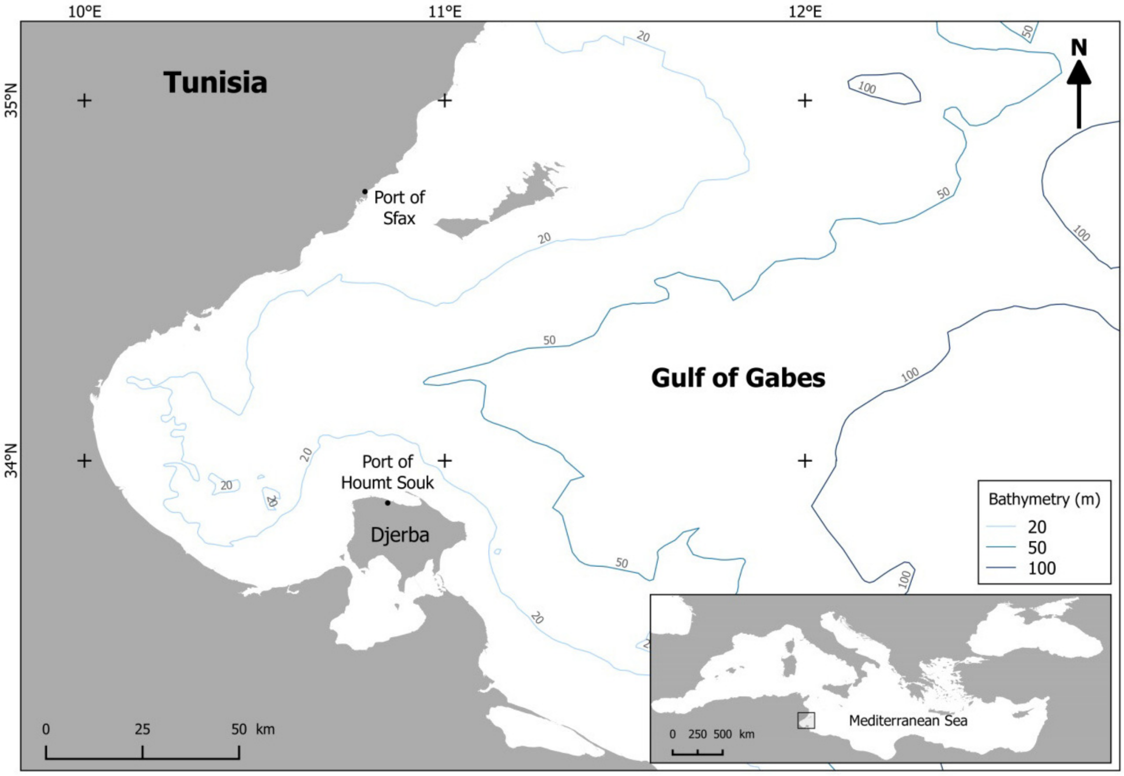

Fig. 1. Geographic location of the study area, the Gulf of Gabes ecosystem.

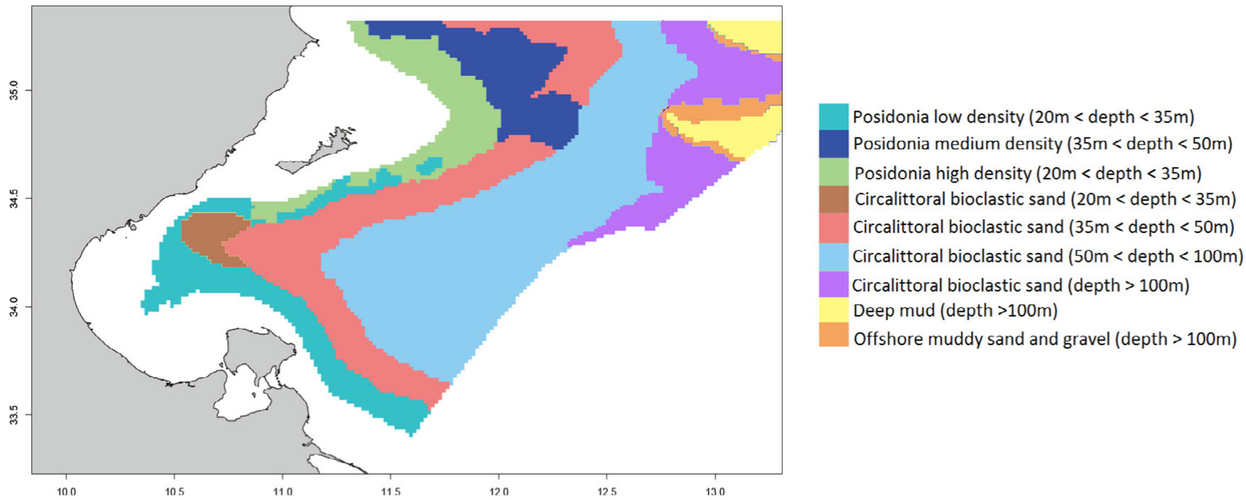

Fig. 2. Spatial extent of the study area and the habitats types included in the Ecospace model.

equation (2):

$$Q_i = P_i + R_i + Q_i GS_i \qquad (2)$$

with R_i the respiration of group i, GS_i the proportion of unassimilated food and Q_i the total consumption rate.

Spatial simulations were based on a trophic model for the Gulf of Gabes that had been created using the Ecopath with Ecosim approach, Version 6.2 (www.ecopath.org; Christensen and Walters 2004; Walters et al. 1999). The model was developed to assess ecosystem functioning and characterize food-web structure during the period 2000–2005. For this model, the area shallower than 20 m was excluded because of lack of reliable data.

The balanced Ecopath model included 62 species divided into 41 functional groups based on ecological and taxonomic similarities (Hattab et al. 2013a). Fisheries in the Gulf of Gabes are considered to be multigear and multispecies (Jabeur et al. 2000). Therefore, the model encompassed six fishery types – bottom trawling, small seines, tuna purse seines, purse seines using lights (lamparos), coastal motorized fishing and sponge fishing. Landings statistics were obtained from DGPA, while discards were taken from the literature (Hattab et al. 2013a). Further details on Ecopath model parameterization can be found in Annex 1 and Hattab et al. (2013a).

The master equation in Ecosim is (Christensen and Walters 2004):

$$\frac{\mathrm{d}B_i}{\mathrm{d}t} = g_i \sum_j Q_{ji} - \sum_j Q_{ji} + I_i - (M0_i + F_i + e_i)\, B_i \qquad (3)$$

where $\frac{\mathrm{d}B_i}{\mathrm{d}t}$ represents the growth rate in mass of group i during time interval dt, g_i is the net growth efficiency (production/consumption ratio), M_i the non-predation natural mortality rate, F_i the fishing mortality rate, e_i the emigration rate, and I_i the immigration rate. The consumption rates are calculated based on the "foraging arena" concept, where the biomass B_i is divided into two compartments: vulnerable and invulnerable (Walters et al. 1997) and the transfer rate (v_i) between those two components determines the type of food web control (top-down, bottom-up or wasp-waist).

The Ecosim approach was used to carry out dynamic simulation using the parameters from the balanced Ecopath model. The Ecosim model was fitted to landings for the period 1995–2008, time series of fishing effort by fishing gear, and stock assessment estimates of functional group biomass (investigations to collect landings data were conducted by the National Institute of Sciences and Technologies of the Sea). In addition, the primary production in the study area for the period 1997–2007 (data from the SeaWIFS project, http://oceancolor.gsfc.nasa.gov/SeaWiFS) was used for calibration (Halouani et al. 2013). To assess goodness-of-fit and robustness of the fitted model, model outputs were compared to landings time series (Annex 2). Then, several established rest period scenarios (temporal fishing closure) were simulated to analyze the response of the ecosystem (Halouani et al. 2013). Because data concerning vulnerability parameters (v_i) could not be found for the study area, an iterative procedure (Monte Carlo) was used to determine their values, which consisted in modifying the vulnerability parameters until the goodness-of-fit was optimized, consequently improving model agreement with available data.

2.3 Ecospace model

Ecospace is the spatially explicit time dynamic module of the Ecopath with Ecosim software (www.ecopath.org; Christensen and Walters 2004; Walters et al. 1999). It integrates the trophic and temporal dynamics of Ecopath and Ecosim across a two-dimensional space.

The first step in implementing an Ecospace model is the definition of spatial grid cells. Each cell represents land or water and is assigned to a specific habitat type (Christensen et al. 2008). Initially, the biomass of functional groups is spread equally and homogeneously across all grid cells. Functional groups move between neighboring grid cells, with movements being controlled by several parameters such as dispersal rate (i.e., the ability of a group to move from one cell to another), foraging behavior (i.e., when functional groups search for their prey) and avoidance of predation (i.e., when functional groups try to avoid being predated) (Walters et al. 1999). The dispersal rate of a group is expressed as distance travelled (km) per year, and it represents the ability of organisms to disperse from a given position through random movements (Christensen et al. 2000). Dispersal rates (V_i) are used to calculate the emigration rate (e_i) for each cell (the rate at which organisms leave the grid cell) based on the following equation: $e_i = \frac{V_i}{\pi L}$, where L is the cell width (Martell et al. 2005). The immigration rate I in equation (3) consists of the four emigration flows from neighboring cells. These flows are calculated using the following formula (Christensen et al. 2014):

$$B_{out,rci} = \sum\nolimits_{d=1}^{4} e_{i,d} * B_{rci} \qquad (4)$$

where $B_{out,rci}$ represents the emigration flow (for the grid cell in row r and column c), $e_{i,d}$ expresses the emigration rate, d is the movement direction, and B_{rci} is the biomass density of group i.

2.4 Ecospace model parameterization

The spatial domain of the Ecospace model covered the entire Gulf of Gabes. The baseline map was drawn on approximately 25 000 square cells, each covering an area of 3.2 km^2. The modeled area extended from the 20-m contour depth to approximately the 200-m isobaths, and included nine habitat types based on depth and bottom type (Hattab et al. 2013b) (Fig. 2). After the habitats were defined, two maps representing depth and relative primary production were related to the baseline map (Christensen et al. 2008). The relative primary production map was drawn based on the average concentration of chlorophyll-a in the Gulf of Gabes by averaging monthly SeaWifs images. Each of the 41 functional groups was assigned to its preferred habitat type, i.e. where the feeding rate was high, based on the available information on the ecology and biology of each species and expert advice (Table 1). Six types of fisheries were included in the Gulf of Gabes model, and each was defined and assigned to the fishing zones where they are permitted to fish according to Tunisian fisheries regulations (Table 2).

The distribution of species across the baseline map is governed by dispersal rates, representing the ability of functional groups to move across the spatial grid of the model. For the Gulf of Gabes model, dispersal rates were established based on data available in the literature (Chen et al. 2009; Fouzai et al. 2012; Martell et al. 2005) or the default values recommended by Christensen et al. (2005).

For baseline dispersal rates we used three values: 300 km year^{-1} for pelagic species with high mobility, 30 km year^{-1} for demersal species with medium mobility, and 3 km year^{-1} for non-dispersing species with low mobility (Christensen et al. 2000). The relative dispersal rate in unsuitable habitats represents the number of times that a functional group would multiply their basic dispersal rate to return to its preferred habitats. We assumed multiplication factors ranging from 1 to 5, depending on the mobility of the species. The relative vulnerability to predation in unsuitable habitats is assumed to be equal to two, implying that species are twice as vulnerable to predation in unsuitable habitats (Christensen et al. 2000). Relative feeding rates in unsuitable habitats represent the fact that species in non-preferred habitats are less likely to

Table 1. Preferred habitats of functional groups in the Gulf of Gabes Ecospace model. (+) sign indicates the assigned habitats.

	Habitat type (depth range)								
Functional group	Deep mud	Offshore muddy sand and gravel	Circalittoral bioclastic muddy sand				Posidonia high density	Posidonia medium density	Posidonia low density
	(<100 m)	(<100 m)	(<100 m)	(50–100 m)	(35–50 m)	(20–35 m)	(20–35 m)	(35–50 m)	(20–35 m)
Phytoplankton	+	+	+	+	+	+	+	+	+
Macro-algae					+	+	+	+	+
Posidonia oceanic							+	+	+
Micro- and mesozooplankton	+	+	+	+	+	+	+	+	+
Macrozooplankton	+	+	+	+	+	+	+	+	+
Foraminifera	+	+	+	+	+	+	+	+	+
Invertebrate suspension feeders	+	+	+	+	+	+	+	+	+
Polychaetes	+	+	+	+	+	+	+	+	+
Amphipoda and Isopoda	+	+	+	+	+	+	+	+	+
Echinoderms	+	+	+	+	+	+	+	+	+
Benthic mollusks	+	+	+	+	+	+	+	+	+
Crabs	+	+	+	+	+	+	+	+	+
Benthic cephalopods	+	+	+	+	+	+	+	+	+
Benthopelagic cephalopods	+	+	+	+	+	+	+	+	+
Mantis shrimp				+	+	+	+	+	+
Caramote prawn				+	+	+	+	+	+
Alien shrimps				+	+	+	+	+	+
Deep shrimps	+	+	+	+					
Horse mackerel	+	+	+	+	+	+	+	+	+
European pilchard	+	+	+	+	+	+	+	+	+
Round sardinella	+	+	+	+	+	+	+	+	+
European anchovy	+	+	+	+	+	+	+	+	+
Picarel	+	+	+	+	+	+	+	+	+
Bogue	+	+	+	+	+	+	+	+	+
Benthic invertebrate feeders (1)	+	+	+	+	+	+	+	+	+
Benthic invertebrate feeders (2)	+	+	+	+	+	+	+	+	+
Mullets	+	+	+	+	+	+	+	+	+
Piscivorous Fish	+	+	+	+	+	+	+	+	+
Sparidae				+	+	+	+	+	+
Macro-carnivorous Fish (1)	+	+	+	+	+	+	+	+	+
Macro-carnivorous Fish (2)	+	+	+	+	+	+	+	+	+
Rays (1)	+	+	+	+	+	+	+	+	+
Rays (2)	+	+	+	+	+	+	+	+	+
Sharks	+	+	+	+	+	+	+	+	+
Small tuna	+	+	+	+	+	+	+	+	+
Medium pelagic fish	+	+	+	+	+	+	+	+	+
Atlantic bluefin tuna	+	+	+	+	+	+	+	+	+
Dolphins	+	+	+	+	+	+	+	+	+
Sea birds	+	+	+	+	+	+	+	+	+

Table 2. Suitability of habitat types for fishing fleets in the Gulf of Gabes Ecospace model. (+) sign indicates fishable habitat.

	Habitat type (depth range)								
Fishing fleet	Deep mud	Offshore muddy sand and gravel	Circalittoral bioclastic muddy sand				Posidonia high density	Posidonia medium density	Posidonia low density
	(<100 m)	(<100 m)	(20-35 m)	(35–50 m)	(50–100 m)	(<100 m)	(20–35 m)	(35–50 m)	(20–35 m)
Coastal fishing			+	+	+		+	+	+
Lamparo	+	+		+	+	+		+	
Small seine	+	+	+	+	+	+	+	+	+
Tuna purse seine	+	+		+	+	+		+	
Bottom trawling	+	+			+	+			
Sponge fishing			+				+		+

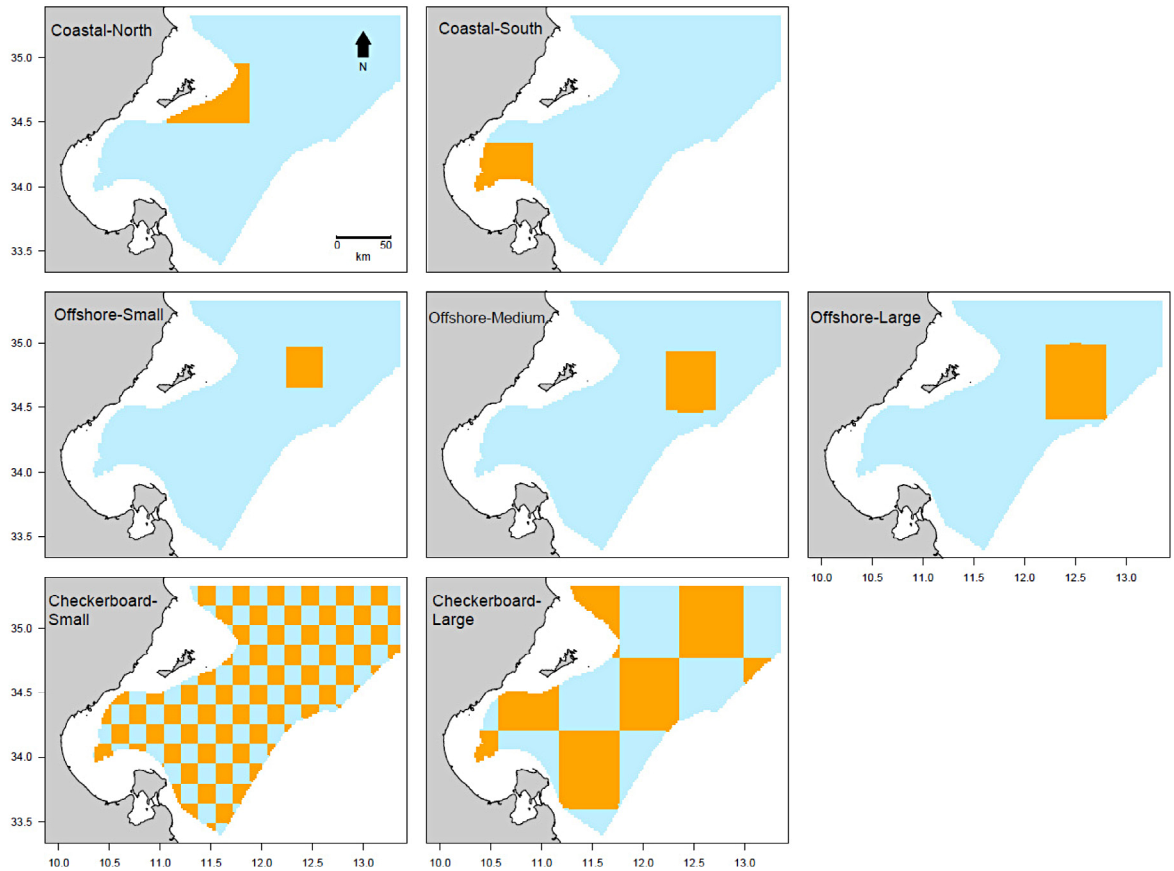

Fig. 3. Maps for spatial distribution of MPAs for the scenarios compared in this study. Orange represents the MPA, blue and orange the study area, and grey land.

find and consume appropriate food. We assumed the following values: 0.95 for functional groups with a trophic level equal to 1 (primary producers) because the habitat type slightly influences the feeding ability of these organisms, 0.01 for species with a trophic level between 2 and 3.5, 0.3 for species with a trophic level between 3.5 and 4, and 0.6 for species with a trophic level greater than 4 (Fouzai et al. 2012) (see Annex 3 for details).

2.5 Spatial management scenarios

Three sets of spatial scenarios were tested for the location of MPAs from which all types of fishing are excluded (Fig. 3). All scenarios were applied over the period 1995–2010. The results were compared to the reference scenario with no MPA, reflecting the present situation in the Gulf of Gabes, to explore the potential effects of the establishment of an MPA on the ecosystem. Note that the studied MPA designs do not reflect desired or planned management plans, but rather represent contrasting scenarios for the spatial distribution of closed areas.

- Coastal MPAs. In the Coastal-North scenario, an MPA covering 1900 km^2 is implemented in the Northern part of the gulf while in the Coastal-South scenario the same surface is protected further to the South (Fig. 3). The aim of these scenarios was to assess the effect of MPA location.
- Offshore MPAs. Three offshore MPA scenarios with different surface areas were implemented, Offshore-Small covering an area of 1300 km^2, Offshore-Medium 2600 km^2, and Offshore-Large 3900 km^2 (Fig. 3). These scenarios provided insight into the importance of MPA size.
- Checkerboard MPAs. Two regular checkerboard configurations were assessed, with many small MPAs for Checkerboard-Small and fewer larger MPAs for Checkerboard-Large (Fig. 3). These scenarios were used to investigate the role of MPA size and distribution.

For all scenarios total biomass by functional group and catches in 2010 were compared to the values obtained for the reference scenario.

3 Results

3.1 Reference scenario

After simulating the reference scenario (no MPA) for 15 years, total species biomass and total catches were 17% and 19% lower respectively compared to the beginning of the period (Table 3). The results showed changes in biomass for functional groups of commercial and ecological importance, with severe declines in cephalopod groups, mantis shrimp, caramote prawn, and deep shrimp (Table 3). The majority of

Table 3. Ecospace simulation results for reference scenario (no MPA). Biomass and catch values by functional group. Biomass values are expressed in t.km^2 and catch value in t.km^2.y^{-1}. Red represents a decrease and green represents an increase of biomasses and catches in 2010 compared to 1995.

Functional group	Biomass (1995)	Biomass (2010)	Biomass ratio (2010/1995)	Catch (1995)	Catch (2010)	Catch ratio (2010/1995)
Phytoplankton	5.54	5.18	0.93			
Macro-algae	1.34	1.16	0.86			
Posidonia oceanica	0.02	0.01	0.70			
Micro- and mesozooplankton	6.45	6.81	1.06			
Macrozooplankton	2.90	2.33	0.80			
Foraminifera	0.34	0.48	1.41			
Invertebrate suspension feeders	6.51	4.61	0.71	0.04	0.07	1.60
Polychaetes	3.95	4.09	1.04			
Amphipoda and Isopoda	4.60	3.19	0.69	0.00	0.00	1.36
Echinoderms	4.26	2.37	0.56	0.03	0.02	0.85
Benthic molluscs	3.92	3.10	0.79	0.01	0.01	1.42
Crabs	2.20	1.39	0.63	0.01	0.00	0.69
Benthic cephalopods	0.27	0.12	0.43	0.10	0.07	0.67
Benthopelagic cephalopods	0.07	0.04	0.58	0.00	0.00	0.85
Mantis shrimp	0.59	0.30	0.51	0.10	0.00	0.05
Caramote prawn	0.12	0.03	0.27	0.13	0.01	0.07
Alien shrimps	0.12	0.20	1.62	0.04	0.02	0.68
Deep shrimps	0.01	0.00	0.25	0.01	0.01	0.60
Horse mackerel	1.50	1.06	0.70	0.03	0.02	0.86
European pilchard	3.55	2.47	0.70	0.17	0.15	0.89
Round sardinella	1.76	1.34	0.76	0.24	0.29	1.20
European anchovy	0.65	0.58	0.89	0.00	0.01	1.63
Picarel	0.59	0.70	1.20	0.02	0.03	2.07
Bogue	0.50	0.42	0.84	0.03	0.03	1.13
Benthic invertebrate feeders (1)	0.22	0.39	1.75	0.06	0.05	0.80
Benthic invertebrate feeders (2)	0.05	0.05	0.98	0.01	0.02	1.19
Mullets	0.10	0.10	1.00	0.07	0.04	0.60
Piscivorous Fish	0.07	0.06	0.83	0.00	0.00	1.69
Sparidae	0.19	0.11	0.59	0.03	0.03	0.95
Macro-carnivorous Fish (1)	0.20	0.14	0.71	0.06	0.04	0.70
Macro-carnivorous Fish (2)	0.05	0.04	0.79	0.01	0.01	0.65
Rays (1)	0.36	0.30	0.82	0.01	0.01	1.41
Rays (2)	0.13	0.08	0.60	0.00	0.00	1.04
Sharks	0.19	0.09	0.47	0.01	0.01	0.81
Small tuna	0.08	0.05	0.67	0.03	0.02	0.71
Medium pelagic fish	1.47	1.22	0.83	0.09	0.09	1.02
Atlantic bluefin tuna	0.23	0.21	0.88	0.06	0.04	0.64
Dolphins	0.08	0.05	0.66			
Sea birds	0.00	0.00	0.63			
Discards	0.36	0.26	0.74			
Detritus	23.20	20.49	0.88			
Total	78.77	65.64	0.83	1.39	1.12	0.81

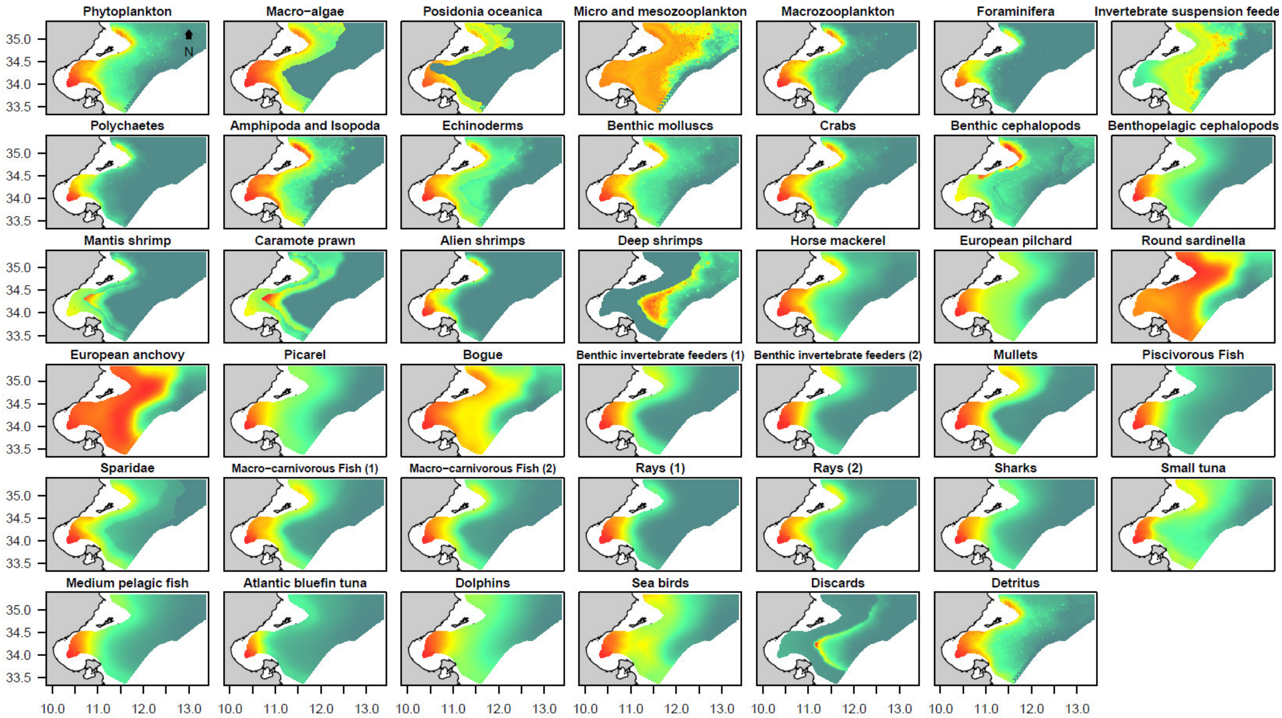

Fig. 4. Ecospace model predictions of the spatial distribution of biomass for each functional group in the Gulf of Gabes at the end of the 15-year simulation period (2010) for the reference scenario with no MPA. Colors represent relative densities in t.km^{-2}.

predator groups exhibited a major decline in biomass, which was most acute for sharks; using the Ecopath model it has been shown that sharks are a keystone group in the Gulf of Gabes ecosystem (Hattab et al. 2013a). However, some exceptions can be noted with some groups having marginally increased biomass. The spatial distribution of functional groups at the end of the simulation period (2010) revealed local depletions of several species, especially in the open sea (Fig. 4).

Regarding catches, many groups showed an increase over the simulation period with catches being multiplied by a factor between 1.2 to 2.5 for groups with an intermediate trophic level such as round sardinella, European anchovy, picarel and bogue (Table 3). However, catches for other groups declined, especially for the commercially targeted demersal species (rays and sharks).

3.2 MPAs implementation simulations

Coastal MPA scenarios

Total biomass for the Coastal-North MPA scenario at the end of the simulation period was nearly identical (–0.05%) to the biomass obtained for the reference scenario (Table 4). However, the biomass of several species was larger when the MPA was implemented, such as for benthic invertebrate feeders (2) (+14%), picarel (+6%), small tuna (+2.5%), sharks (+2%), medium pelagic fish (+1.5%) and Atlantic bluefin tuna (+1.2%). In contrast, other groups responded to the MPA with a decline in their biomasses, such as caramote prawn (–11%), mullets (–5%), mantis shrimp (–4%), macro-carnivorous fish (2) (–2%) and alien shrimp (–1.6%). The establishment of the MPA led to an 11% increase in the total catch with a substantial increase in the catches for all groups, except European pilchard, round sardinella, European anchovy and bogue (Table 4).

The results for the Coastal-South MPA scenario were similar with basically no change (+0.11%) in total biomass and larger biomasses, especially for commercially targeted groups of benthic invertebrate feeders (2) (+89%), piscivorous fish (+38%), rays (1) (+14%), Atlantic bluefin tuna (+5%), small tuna (+3%) and medium pelagic fish (+2.5%). Similar functional groups exhibited a lower biomass, such as macro-carnivorous fish (1) (–5%) and (2) (–8%), mantis shrimp (–5.5%), caramote prawn (–5%), sparidae (–2.5%), picarel (–2.5%), European pilchard (–2%) and mullets (–2%). Total catches were 4% lower for this coastal MPA scenario, and the decline concerned nearly all functional groups, except benthic invertebrate feeders (2), piscivorous fish and European anchovy (Table 4).

Comparing the two implementations of a coastal MPA showed a difference in the response of functional groups. For several groups, the increase in biomass, compared to the reference scenario, was more pronounced when implementing the Coastal-North MPA than the scenario with the Coastal-South MPA. For instance, benthic invertebrate feeders (2) exhibited a 14% increase in the first scenario and 89% in the second. The biomass of the piscivorous fish group did not change in the Coastal-North MPA while it increased by 38% for the southern MPA. For some other groups, biomass increased when implementing the Coastal-North MPA and decreased for the

Table 4. Ecospace simulation results for MPA scenarios compared to the reference scenario (no MPA). Biomass and catch ratios at the end of the simulation period (2010) by functional group. Red represents less (ratio < 0.99) and green higher (ratio > 1.01) biomass or catch. For scenario description see Figure 3.

	Biomass							Catch						
Functional group	Coastal-North	Coastal-South	Offshore-Small	Offshore-Medium	Offshore-Large	Checker board-Small	Checker board-Large	Coastal-North	Coastal-South	Offshore-Small	Offshore-Medium	Offshore-Large	Checker board-Small	Checker board-Large
Phytoplankton	1.0002	1.0006	1.0000	1.0000	0.9999	1.0002	1.0012							
Macro-algae	1.0060	1.0105	0.9989	0.9968	0.9953	1.0056	1.0142							
Posidonia oceanica	1.0174	1.0274	1.0031	1.0022	1.0021	1.0106	1.0513							
Micro- and mesozooplankton	0.9986	1.0019	0.9991	0.9990	0.9990	1.0007	1.0021							
Macrozooplankton	0.9889	0.9940	0.9994	1.0009	1.0022	0.9963	0.9785							
Foraminifera	1.0074	1.0283	0.9981	0.9965	0.9950	1.0063	1.0385							
Invertebrate suspension feeders	1.0087	1.0202	1.0009	1.0015	1.0021	1.0084	1.0463	1.1606	1.0040	0.9793	0.9945	1.0052	0.9895	0.8246
Polychaetes	0.9983	0.9743	1.0007	1.0012	1.0016	0.9945	0.9718							
Amphipoda and Isopoda	1.0007	1.0000	1.0009	1.0020	1.0031	0.9992	0.9992	1.0225	0.9517	0.9962	0.9838	0.9783		
Echinoderms	0.9729	0.9807	0.9916	0.9909	0.9888	0.9770	0.8780	1.1052	0.9837	0.9947	1.0200	1.0403	0.8658	0.6585
Benthic molluscs	1.0003	1.0048	0.9985	0.9978	0.9970	1.0008	1.0024	1.0716	0.9426	0.9947	0.9891	0.9889	0.8851	0.7794
Crabs	0.9928	0.9824	0.9992	0.9998	1.0000	0.9903	0.9587	1.1638	1.0005	1.0118	1.0389	1.0676	0.9756	0.8395
Benthic cephalopods	0.9874	0.9895	0.9971	0.9967	0.9940	0.9787	0.9452	1.0792	0.9752	0.9848	0.9775	0.9983	0.6823	0.4565
Benthopelagic cephalopods	1.0031	1.0000	0.9976	0.9920	0.9876	1.0069	1.0220	1.1590	0.9335	1.0075	1.0239	1.0387	0.8377	0.6755
Mantis shrimp	0.9644	0.9454	1.0019	1.0033	1.0062	1.0051	0.9281	1.4217	1.0014	1.0299	1.0734	1.0853	1.3052	0.7896
Caramote prawn	0.8934	0.9513	1.0347	1.0115	1.0122	1.1200	1.2303	1.3145	0.8956	1.0298	1.0965	1.1240	0.9668	0.5681
Alien shrimps	0.9842	0.9544	1.0000	0.9995	1.0006	0.9885	0.9561	1.3855	0.7106	1.0345	1.0705	1.0822	0.0376	0.0343
Deep shrimps	1.0019	1.0009	0.9772	0.9643	0.9513	0.9214	0.8081	1.0855	1.0012	0.9798	0.9895	1.0007	0.7972	0.5724
Horse mackerel	0.9927	0.9973	0.9982	0.9984	0.9984	0.9977	0.9831	1.0079	0.9392	1.0085	1.0233	1.0376	1.0445	0.9430
European pilchard	1.0010	1.0198	0.9975	0.9943	0.9916	1.0093	1.0428	0.9897	0.9604	1.0058	1.0156	1.0236	1.3205	1.1899
Round sardinella	0.9941	1.0029	0.9980	0.9976	0.9969	1.0022	0.9958	0.9785	0.9963	0.9938	0.9971	0.9987	1.1852	1.0254
European anchovy	0.9953	1.0008	0.9985	0.9993	0.9998	1.0004	0.9998	0.9912	1.0107	0.9969	1.0019	1.0050	1.0963	0.9762
Picarel	1.0601	0.9742	1.0112	1.0084	1.0063	1.0016	1.0381	1.2330	0.9581	1.0108	1.0179	1.0241	0.8900	0.7835
Bogue	0.9961	0.9977	0.9987	0.9993	0.9996	0.9993	0.9933	0.9927	0.9819	0.9986	1.0044	1.0095	1.3420	1.2257
Benthic invertebrate feeders (1)	1.0117	0.9417	1.0193	1.0246	1.0343	1.0032	1.1352	1.4792	0.9689	1.0035	1.0164	1.0236	0.9410	0.8622
Benthic invertebrate feeders (2)	1.1398	1.8893	0.9716	0.9467	0.9252	1.1891	2.0725	1.3130	1.3008	0.9702	0.9541	0.9381	0.3731	0.4411
Mullets	0.9534	0.9766	1.0134	1.0173	1.0249	1.0052	1.1329	1.2948	0.9637	0.9954	1.0170	1.0359	0.8458	0.6784
Piscivorous Fish	1.0034	1.3815	0.9935	0.9865	0.9807	1.0416	1.2356	1.0425	1.0542	0.9972	0.9947	0.9919	0.5490	0.5603
Sparidae	0.9984	0.9762	1.0011	1.0027	1.0036	0.9971	0.9678	1.0679	0.8780	1.0048	1.0090	1.0102	0.6616	0.6234
Macro-carnivorous Fish (1)	1.0051	0.9510	1.0079	1.0132	1.0199	0.9979	1.0377	1.2839	0.9418	0.9968	1.0088	1.0168	0.7946	0.6171
Macro-carnivorous Fish (2)	0.9804	0.9201	1.0083	1.0158	1.0234	0.9706	0.9354	1.2873	0.9543	0.9921	1.0053	1.0148	0.8873	0.6560
Rays (1)	1.0026	1.1378	0.9937	0.9891	0.9846	1.0201	1.0914	1.1800	0.7352	1.0075	1.0120	1.0166	0.1576	0.1241
Rays (2)	1.0101	0.9929	0.9992	0.9974	0.9960	1.0001	0.9963	1.1486	0.8509	1.0084	1.0190	1.0287	0.4814	0.3438
Sharks	1.0205	0.9539	1.0021	1.0004	0.9993	1.0055	1.0167	1.1838	0.8155	1.0095	1.0164	1.0287	0.4999	0.4001
Small tuna	1.0239	1.0287	0.9981	0.9963	1.0012	1.0190	1.0668	0.9974	0.9364	0.9970	0.9990	1.0032		
Medium pelagic fish	1.0152	1.0235	1.0011	1.0022	1.0060	1.0089	1.0352	1.0157	0.9564	1.0021	1.0031	1.0030	1.2069	1.1322
Atlantic bluefin tuna	1.0117	1.0496	1.0041	1.0169	1.0386	1.0385	1.2342	1.0002	0.9827	1.0038	1.0125	1.0203		
Dolphins	1.0082	1.0024	0.9999	0.9981	0.9967	1.0052	1.0231							
Sea birds	1.0190	1.1186	1.0016	1.0010	1.0020	0.9630	1.0574							
Discards	0.9617	0.9816	0.9934	1.0040	1.0099	0.9996	0.8690							
Detritus	1.0000	1.0003	0.9999	0.9998	0.9996	1.0002	1.0006							
Total	0.9995	1.0011	0.9996	0.9996	0.9997	1.0003	1.0011	1.1068	0.9658	1.0031	1.0184	1.0286	0.6460	0.5644

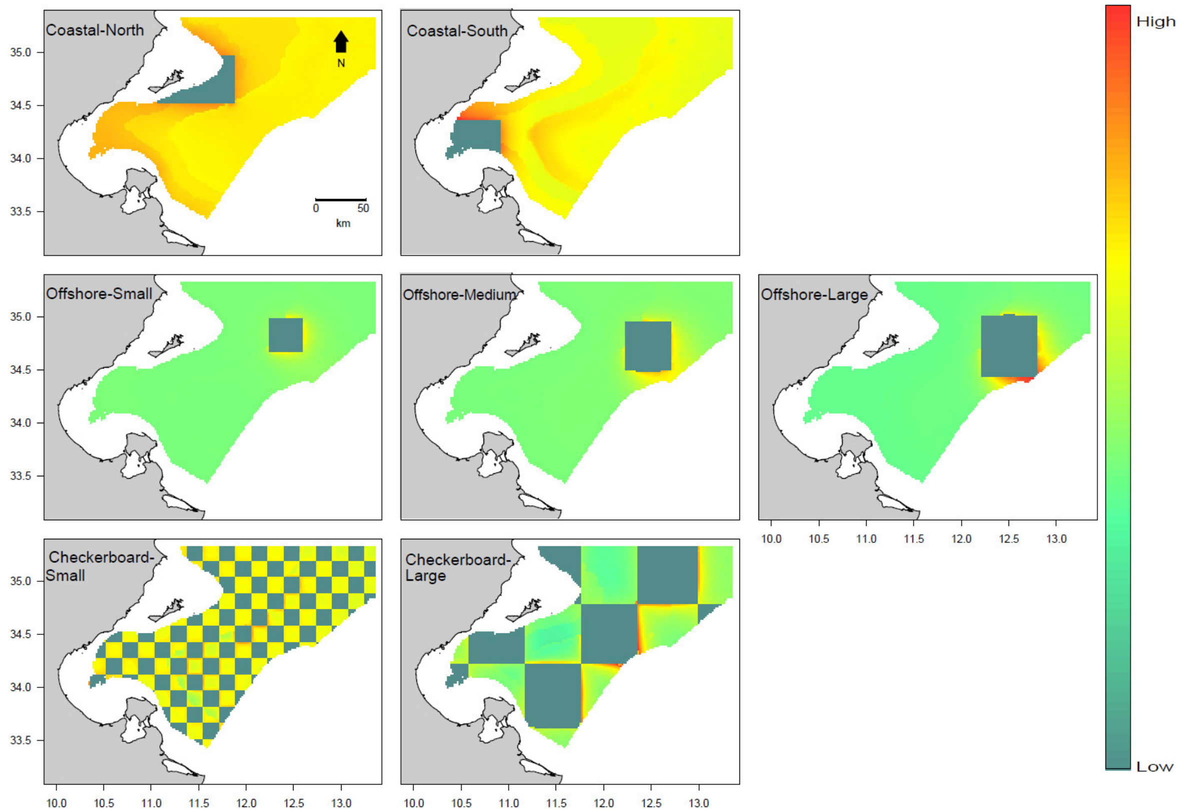

Fig. 5. Spatial distribution of the total catches in the Gulf of Gabes ecosystem at the end of the simulation period (2010) for different MPA scenarios; see Figure 3 for a description of scenarios. MPAs closed to fishing are represented in blue.

Coastal-South MPA, such as picarel (+6% vs. –2.5%), benthic invertebrate feeders (1) (+1.2% vs. –6%) and sharks (+2% vs. –5%). Total catches increased by +11% for the Coastal-North scenario and decreased by –4% for the northern MPA. The catches of the majority of functional groups increased for the Coastal-North scenario, while they decreased for the Coastal-South scenario. This difference was marked for alien shrimp with a +38% increase in catches for the northern MPA compared to a 29% decrease for the southern MPA.

Offshore MPA scenarios

The main purpose of these offshore MPA scenarios was to understand the effect of MPA size on functional group biomass and catches. In response to the implementation of the three different-sized MPAs, some groups benefitted from MPA size expansion, such as benthic invertebrate feeders (1), mullets, Atlantic bluefin fish and macro-carnivorous fish (1) and (2). The implementation of the MPA resulted in a decline in the biomass of some groups, such as deep shrimps, benthic invertebrate feeders (2), piscivorous fish and rays (1). Furthermore, total biomass decreased compared to the reference scenario, 0.4%, 0.4% and 0.3% respectively for increasing MPA size. Regarding catches, in total, the harvested biomass increased with MPA size, by +0.3%, +1.8% and +2.9% respectively, and this was the general trend for the majority of the groups, except benthic invertebrate feeders (2) (Table 4).

Checkerboard MPA scenarios

For these scenarios, the same surface area was protected using a checkerboard pattern but with differences with respect to the size of each MPA (many small or fewer large). The outcomes showed that, for most groups, final year biomass was larger compared to the reference scenario, with the exception of alien shrimp, deep shrimp, mantis shrimp, horse mackerel, Sparidae, macro-carnivorous fish and sea birds. The differences were more marked for the Checkerboard-Large scenario, which had fewer larger MPAs. However, the difference in the total biomass increase was small (+0.03% compared to +0.11%).

Concerning total catch, a significant decrease was found for both scenarios (–35% and –44% respectively). This could be explained by the fact that approximately half of the Gulf of Gabes was protected in both scenarios. The catches of some groups increased for small-sized MPAs, but decreased for the larger MPAs, e.g. for mantis shrimp, horse mackerel and European anchovy. For most groups the decrease in catches was much more marked when the checkerboard consisted of larger MPAs (Table 4).

Spatial distribution of total catch and biomass

To explore the redistribution of fishing efforts when an MPA was implemented, maps were drawn for the spatial distribution of total catches at the end of the simulation period (2010) for each investigated scenario (Fig. 5). The results

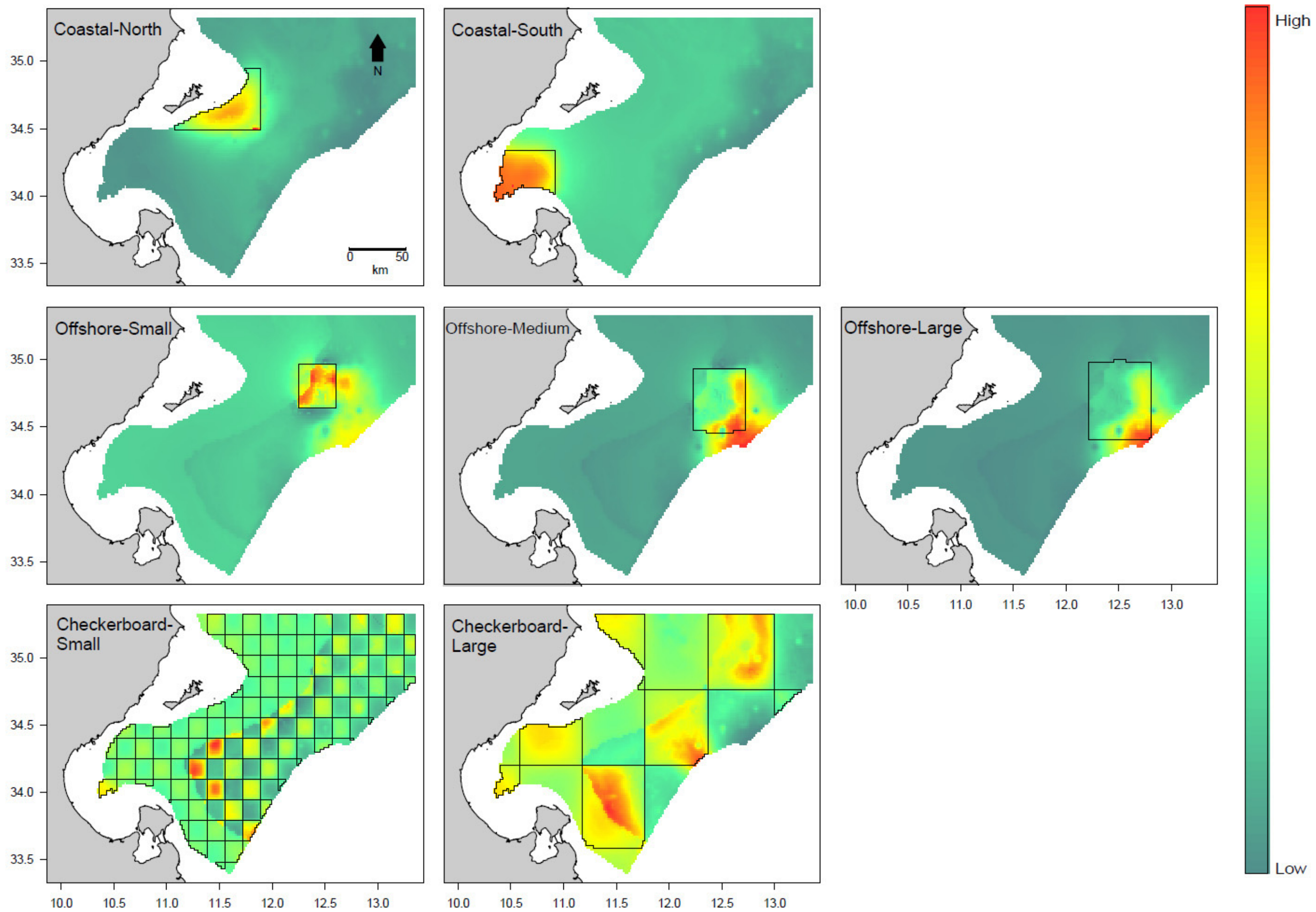

Fig. 6. Spatial distribution of the total biomass in the Gulf of Gabes ecosystem at the end of the simulation period (2010) for different MPA scenarios; see Figure 3 for a description of scenarios. Boxes delimit MPAs closed to fishing.

showed a concentration of catches and thus fishing activity in the areas adjacent to the MPAs, with the degree of increase in catches next to MPAs differing between scenarios, indicating differences in the "spillover" effect. The spatial distribution of total biomass was also mapped (Fig. 6). Total biomass was always higher inside the MPAs and in the adjacent areas, but with differences between scenarios.

4 Discussion

Recognizing the global depletion of fish resources, it has become necessary to develop adequate complementary methods for managing fisheries (Halpern et al. 2008; Pitcher and Cheung 2013). To this end, modeling is considered a valuable tool to help make decisions for conserving and exploiting marine resources (Christensen and Walters 2004). This study uses a spatio-temporal modeling framework to evaluate the effects generated by the establishment of MPAs on ecosystem structure, through trophic cascades and links between different functional groups. The model also provided insights into how species-specific biomasses and catches could change for each of the tested management scenarios.

For the Northern-Central Adriatic Sea ecosystem Fouzai et al. (2012) simulated realistic MPA scenarios using an Ecospace model. In contrast, the scenarios assessed in this study cannot be implemented and were only intended to help understand the ecosystem. Another major difference is that the Adriatic Ecospace model scenarios simulated a seasonal fishing ban and a reduction in fishing effort while here we only explored permanent fishing bans and status quo fishing effort.

Current fishery state

The results of this study indicated that given the current fishery state in the Gulf of Gabes, the depletion of marine resources was more severe in 2010, i.e. at the end of the 15-year simulation period. This conclusion agrees with what was deduced from the Ecopath model by Hattab et al. (2013a), in which all of the assessed indicators showed that the area is unsustainably fished.

The results highlighted that most of the predator species with high and medium trophic levels had lower abundance after the 15-year simulation, which explains the increase in their prey. These results are in agreement with the findings obtained with an Ecotroph model reported in Halouani et al. (2015).

The outcomes of the reference scenario showed a major increase in the biomass of the alien Lessepsian shrimp group (*Trachysalambria curvirostris* and *Metapenaeus monoceros*). This group is in direct trophic competition with the native caramote prawn because both groups have similar prey and predators, leading to a partial trophic niche overlap (Ben Abdallah et al. 2003). As a result of this competitive relationship, a reduction in the biomass of caramote prawn occurred. Other shrimp groups exhibited a similar decline (mantis shrimp and deep shrimp) following the appearance of alien shrimp in massive numbers. In addition, caramote prawn has a high fishing mortality rate because it is the primary target of bottom trawlers. These finding are in agreement with previous conclusions (Ben Abdallah et al. 2003).

The biomass of predator groups exhibited a dramatic decline, primarily among sharks and rays. Sharks play an important role in the Gulf of Gabes ecosystem, and they are primarily a by-catch species for bottom trawlers (Hattab et al. 2013a; Saïdi et al. 2005). Landings in the Gulf of Gabes occur all year round and they primarily consist of juveniles and near-term pregnant females that approach the coast to give birth in more favorable environmental conditions (Saïdi et al. 2008). Based on official landings statistics collated by the DGPA, elasmobranch catches in the Gulf of Gabes region represent 2.24% of national fish production, and elasmobranch production has declined since 2002, despite increased fishing effort in the area.

Scenarios discussion

To safeguard marine resources and help in the recovery of overexploited stocks, MPAs are increasingly promoted as an effective management strategy. Marine reserves provide a precautionary approach to halt the overexploitation of fish stocks (Chen et al. 2009; Murray et al. 1999). MPAs minimize the impact of fisheries on ecosystems by protecting sensitive habitats and providing refuge for endangered species. They also insure better fishery stability by closing the gap between the yield and stock capacity, which can reconstitute itself (Ward et al. 2001). Nonetheless, the implementation of MPAs closed to fishing does not necessarily benefit the ecosystem (Le Quesne et al. 2007), and some unexpected results have been reported. For example, when the conditions within the protected area favor the increase of predator populations, prey biomass will decline, leading to the so-called trophic cascade. In the short term, closed areas can result in lower catches, and fishermen may be obliged to sail further to reach fishing grounds. However, on the economic side, the loss of catches could be compensated for when species with higher commercial values are targeted. Indeed, the benefits within and outside the closed areas might be reached in the long term, after a long period of protection (Abesamis and Russ 2005; Colléter et al. 2014).

Despite their popularity and historical use, field evidence for the impacts of MPAs on species biomass and fishery yields remains elusive. Therefore, ecosystem modeling can help evaluate the effectiveness of management plans before implementation (Hilborn et al. 2006). The Ecospace model can be used to evaluate the effects of a given management option and provide insights into where to place protected areas and how to design them (Salomon et al. 2002).

Comparing the two coastal MPA scenarios with the reference scenario indicated a decrease in total biomass for the more northern MPA, but with an increase in total catch, and an increase in total biomass and a decline in total yield for the more southerly located MPA. Thus, it can be concluded that the location of the MPA influences the benefits gained from MPA establishment, which is directly related to the habitats that occur in the protected area. Several studies have shown that the implementation of a successful MPA requires good knowledge of the location and type of habitats (Dugan and Davis 1993; Friedlander and Parrish 1998; Guizien et al. 2012). This result is also in agreement with the results of Hattab et al. (2013b), who used a new method based on the fuzzy logic framework to identify favorable areas in the Gulf of Gabes in which to place artificial anti-trawling reefs. Their results showed that the choice of the location and the spatial arrangement of the reefs is crucial and should be carefully planned to ensure the intended conservation of the ecosystem (Hattab et al. 2013b).

The primary goal of the offshore MPA scenarios was to consider the influence of MPA size. Accordingly, the implemented MPAs had relative sizes of 1, 2 and 3. Comparing these scenarios with the reference scenario did not show any differences concerning total biomass. In a study conducted by Halpern (2003), in which he reviewed the empirical results of 89 different MPAs to assess the impact of MPAs on different biological measures, the results showed that, on average, the size of the protected area did not influence the increase in species abundances or biomasses. However, for total catch we observed a significant gain when we increased the size of the MPA, multiplying the total catch by 1.0031 for a small offshore MPA, by 1.0184 for a medium-sized MPA and by 1.0286 for a large MPA. This result can be explained by the "gravity model" used in the Ecospace model to distribute fishing effort over the modeled area based on fishing profitability, which allows the model to mimic reality in a more accurate and realistic way (Walters et al. 1999). Furthermore, when an MPA is established, the model redistributes the fishing effort rather than reducing it, resulting in a pronounced concentration of fishing activity in the areas adjacent to the MPA. Therefore, an increase in the size of an MPA results in an increase of the boundary and, consequently, an increase in catches. These patterns were also found for other scenarios (Fig. 5).

With the checkerboard scenarios we assessed the effect of MPA shape by implementing two different MPA networks in a checkerboard pattern covering half of the Gulf of Gabes. The first had many small-sized MPAs and the second fewer large ones. The results showed a large decrease in total catch, due to the prohibition of fishing activity over a large area. We can conclude that many small MPAs benefit the fisheries more than the implementation of fewer large MPAs in terms of total catch. However, no large differences were found for the level of total biomass. This conclusion is in line with what has been shown by Aswani and Hamilton (2004). Many other studies showed that a network of small-size MPAs allows for much better protection of marine communities than one large protected area (Hastings and Botsford 2003; Lubchenco et al. 2003). Indeed, the circumference/surface ratio is higher when many small MPAs are implemented, allowing for greater diffusion of species and propagules in the adjacent areas, which is highly beneficial for fishery (Roberts et al. 2003).

Because MPAs contain more and larger fish, the protected species can potentially produce more than in unprotected areas. From this study it can be concluded that there was a higher concentration of species inside the MPA and in the adjacent areas as a result of the "spillover" effect (Fig. 6). However, we found that the biomass emigrating from the MPA was more pronounced for the southern coastal MPA scenario compared to the northern one, although the size of the MPA remained the same. Indeed, the spillover phenomenon was also related to the types of habitat protected by the MPA. Therefore, in instances when the habitats outside the MPA are suitable for the species inside the protected area, emigration will be greater (as in the Coastal-South scenario) (Tupper 2007). However, in the opposite case, when the adjacent habitats are not as favorable as the ones inside the MPA, the spillover will not have the same intensity and will be lower in terms of biomass (as found for the Coastal-North scenario) (Freeman et al. 2009).

Considering the overall results, the most susceptible groups to change were species with high commercial value and those predominantly targeted by bottom trawlers (benthic invertebrate feeders, mullets, macro-carnivorous fish, piscivorous fish, sharks and rays). Most of these groups are considered to be over- or fully exploited (Ben Meriem et al. 1994; Gharbi et al. 2004; Jarboui et al. 1998); they have an exploitation rate higher than the general reference point (Hattab et al. 2013a). This indicates that the Gulf of Gabes is a highly fished ecosystem. Thus, the establishment of effective management measures (MPAs) is a necessity to remedy the situation.

The results of this study are conditional on a number of factors that might affect the outcomes. First and foremost, there is a strong dependency of the Ecospace model on the underlying Ecopath and Ecosim model. The estimation errors are very large for the parameters of the Ecopath model. Furthermore, given the lack of reliable data the area shallower than the 20-m isobath was excluded, adding more uncertainty to the model results.

The Ecospace model of the Gulf of Gabes did not account for all types of transport processes and excluded migratory behavior and advection due to a lack of data. These factors can be important for the spatial distribution of fish species and their inclusion would provide more accurate and realistic predictions. The study could be completed with a socioeconomic component by defining additional parameters, such as sailing costs and species prices, which would provide an idea about the best management options to halt the depletion of marine resources while maintaining reasonable economic profitability. The robustness of the model could be improved if data concerning the spatial distribution of catches, biomass values and fishing efforts were available. Such data could be used to validate the model.

Although these limitations can potentially compromise the accuracy of the model at a quantitative level, the qualitative information gained from the Ecospace model is still useful and can be utilized by policymakers to make informed decisions (Walters et al. 1999). Finally, the majority of the scenarios assessed in this study are not feasible and do not reflect any planned MPA, but they are a theoretical exercise designed to predict the temporal trends of the ecosystem and to assess its potential response to different management plans.

5 Conclusion

Although the threats to the Gulf of Gabes ecosystem are increasing, this study showed that recovery is possible and the decline of several fish stocks can be stopped only if adequate management plans are implemented. The Ecospace model was implemented to explore the potential effects of different MPA designs.

MPAs are promoted as an effective management tool to support the recovery of ecosystems. They have been widely used to protect vulnerable habitats and to conserve marine biodiversity in an ecosystem-based approach. This study suggests that the implementation of a protected area in the Gulf of Gabes could be simultaneously beneficial for the ecosystem and fishing activities. However, the benefits are directly related to the characteristics of the MPA. Our spatial simulations highlight that the location of the protected area is crucial to the success of the MPA. Additionally, an increase in the size of an MPA can result in an increase in the spillover effect and, consequently, in catches in the neighborhood without harming ecosystem integrity. The configuration of the implemented MPA is of capital importance as well. Indeed, a set of many small MPAs was found to be more beneficial than fewer and larger MPAs, especially in terms of catches, because more habitat types can be protected and the emigration of species towards the unprotected areas will be increased. Another outcome of this study was that the intensity of the spillover from the MPA varies according to the habitat types occurring inside and in the adjacent areas of the MPA.

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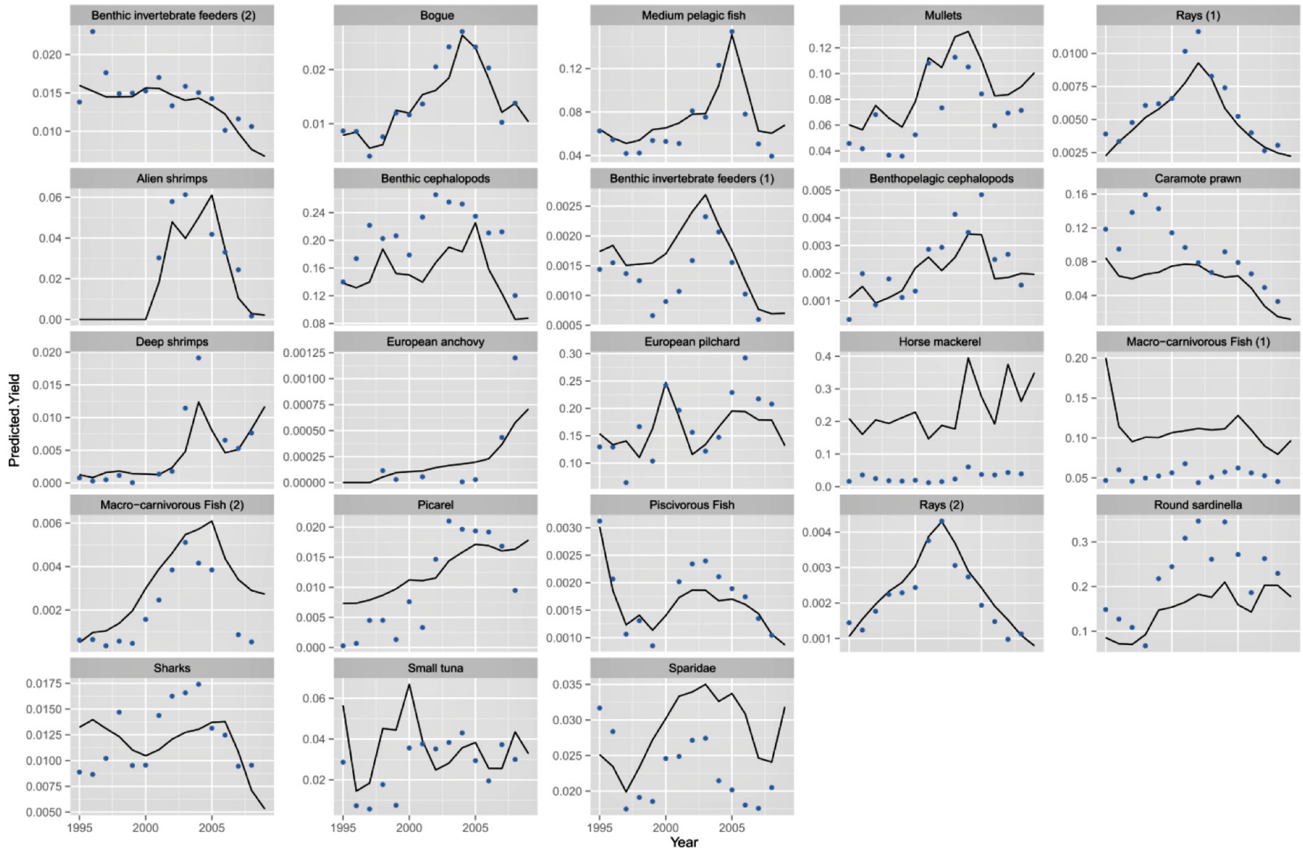
Annex 1. Parameters of the Ecopath model for the Gulf of Gabes ecosystem.

Group name	Trophic level	Biomass (t/km^2)	Production/ biomass (/year)	Consumption/ biomass (/year)	Ecotrophic efficiency	Production/ consumption
Phytoplankton	1.000	7.650	160.000	0.000	0.309	
Macro-algae	1.000	2.188	13.400	0.000	0.950	
Posidonia oceanica	1.000	0.046	15.033	0.000	0.950	
Micro- and mesozooplankton	2.105	8.460	32.395	51.069	0.950	0.634
Macrozooplankton	3.093	3.463	22.650	56.570	0.950	0.400
Foraminifera	2.000	0.368	7.844	23.532	0.950	0.333
Invertebrate suspension feeders	2.725	7.382	1.647	9.904	0.950	0.166
Polychaetes	2.361	4.416	3.502	19.723	0.950	0.178
Amphipoda and Isopoda	2.000	5.464	2.405	26.199	0.950	0.092
Echinoderms	2.327	4.526	0.570	2.460	0.950	0.232
Benthic molluscs	2.353	4.258	1.886	9.386	0.950	0.201
Crabs	3.211	2.089	2.555	4.953	0.950	0.516
Benthic cephalopods	3.701	0.552	2.800	5.642	0.968	0.496
Benthopelagic cephalopods	4.225	0.065	2.712	31.640	0.885	0.086
Mantis shrimp	3.716	0.560	1.590	4.854	0.884	0.328
Caramote prawn	3.279	0.131	2.260	7.665	0.994	0.295
Alien shrimps	2.868	0.125	3.800	7.665	0.996	0.496
Deep shrimps	3.270	0.036	2.796	7.665	0.952	0.365
Horse mackerel	3.663	1.550	0.716	9.044	0.997	0.079
European pilchard	3.122	3.829	1.116	11.403	0.927	0.098
Round sardinella	3.125	1.850	0.853	9.635	0.953	0.089
European anchovy	3.081	0.700	1.089	10.505	0.882	0.104
Picarel	3.104	0.618	0.882	27.280	0.791	0.032
Bogue	3.200	0.538	0.772	19.813	0.782	0.039
Benthic invertebrate feeders (1)	3.537	0.210	0.608	6.834	0.997	0.089
Benthic invertebrate feeders (2)	3.391	0.049	0.723	8.529	0.946	0.085
Mullets	3.305	0.085	1.310	6.587	0.990	0.199
Piscivorous Fish	4.213	0.067	0.359	4.335	0.788	0.083
Sparidae	3.313	0.216	0.779	7.832	0.959	0.099
Macro-carnivorous Fish (1)	4.026	0.189	0.639	9.380	0.999	0.068
Macro-carnivorous Fish (2)	4.056	0.052	0.571	8.529	0.949	0.067
Rays (1)	4.060	0.363	0.239	3.277	0.095	0.073
Rays (2)	3.780	0.133	0.342	3.736	0.267	0.092
Sharks	4.355	0.193	0.544	4.233	0.220	0.128
Small tuna	4.419	0.074	0.591	8.193	0.950	0.072
Medium pelagic fish	4.118	1.462	0.111	1.306	0.891	0.085
Atlantic bluefin tuna	4.381	0.230	0.313	3.513	0.899	0.089
Dolphins	4.339	0.080	0.075	14.361	0.000	0.005
Sea birds	3.772	0.002	0.200	62.751	0.000	0.003
Discards	1.000	0.381			0.447	
Detritus	1.000	30.000			0.280	



Annex 2. Comparison between time series of landings (points) and model outputs (lines) for the period 1995–2008.

Annex 3. Input parameters used in the Gulf of Gabes Ecospace model for each functional group.

Functional group	Trophic level	Baseline dispersal rate (km/year)	Relative dispersal rate in unsuitable habitat	Relative vulnerability to predation in unsuitable habitat	Relative feeding rate in unsuitable habitat
Phytoplankton	1.00	3	1	2	0.95
Macro-algae	1.00	3	1	2	0.95
Posidonia oceanic	1.00	3	1	2	0.95
Micro- and mesozooplankton	2.10	3	1	2	0.01
Macrozooplankton	3.09	3	1	2	0.01
Foraminifera	2.00	3	1	2	0.01
Invertebrate suspension feeders	2.72	3	1	2	0.01
Polychaetes	2.36	3	1	2	0.01
Amphipoda and Isopoda	2.00	3	1	2	0.01
Echinoderms	2.32	3	1	2	0.01
Benthic mollusks	2.35	3	2	2	0.01
Crabs	3.21	3	2	2	0.01
Benthic cephalopods	3.70	3	2	2	0.30
Benthopelagic cephalopods	4.22	3	2	2	0.60
Mantis shrimp	3.71	30	2	2	0.30
Caramote prawn	3.27	30	2	2	0.01
Alien shrimps	2.86	30	2	2	0.01
Deep shrimps	3.27	30	2	2	0.01
Horse mackerel	3.71	300	3	2	0.30
European pilchard	3.12	300	3	2	0.01
Round sardinella	3.12	300	3	2	0.01
European anchovy	3.08	300	3	2	0.01
Picarel	3.10	300	3	2	0.01
Bogue	3.20	300	3	2	0.01
Benthic invertebrate feeders (1)	3.53	300	3	2	0.30
Benthic invertebrate feeders (2)	3.39	300	3	2	0.01
Mullets	3.30	300	2	2	0.01
Piscivorous Fish	4.21	300	3	2	0.60
Sparidae	3.35	300	4	2	0.01
Macro-carnivorous Fish (1)	4.02	300	4	2	0.60
Macro-carnivorous Fish (2)	4.05	300	4	2	0.60
Rays (1)	4.06	30	4	2	0.60
Rays (2)	3.78	30	4	2	0.30
Sharks	4.35	300	5	2	0.60
Small tuna	4.45	300	5	2	0.60
Medium pelagic fish	4.12	300	5	2	0.60
Atlantic bluefin tuna	4.43	300	5	2	0.60
Dolphins	4.34	300	5	2	0.60
Sea birds	3.77	300	5	2	0.30

Évaluation des impacts environnementaux du chalutage de fond et de l'aquaculture en Tunisie: approche comparative par les Analyses de Cycle de Vie (ACV)

L'aquaculture et la pêche impactent l'environnement, les ressources et le fonctionnement des écosystèmes. L’un des enjeux en écologie est de placer ces activités anthropiques dans un cadre de développement durable. Afin de quantifier et de limiter ces impacts, différentes méthodes d’évaluation environnementale ont vu le jour. L’Analyse de Cycle de Vie (ACV) est une méthode pertinente pour évaluer le bilan environnemental d'un produit en prenant en compte l’ensemble de ses étapes de vie, "du berceau à la tombe", depuis l’extraction des matières premières et leurs transformations pour l'élaboration du produit, jusqu’à la fin de vie. Cette thèse porte sur l’adaptation de l’ACV au domaine de l'aquaculture et de la pêche en Tunisie. Son objectif est d'explorer les perspectives offertes par cette méthodologie afin de mieux caractériser le fonctionnement des systèmes de production de poissons et leur lien avec l’environnement. Cette étude a montré que les pratiques aquacoles et la production d'aliment de poisson sont les contributeurs majeurs aux impacts environnementaux, ceci est expliqué par l'utilisation de farine et d'huile de poisson dans la fabrication de l'aliment. Les résultats ont également montré que les impacts du chalutage de fond sont proportionnels à la quantité de carburant nécessaire pour la production. Ce travail a permis d'étudier et comparer les impacts environnementaux de l'activité aquacole et de la pêche au chalutage de fond en Tunisie. Les résultats de cette thèse ont un intérêt pour les gestionnaires en proposant des voies d'amélioration et des recommandations stratégiques de gestion pour améliorer les deux secteurs afin de les placer dans un contexte de développement durable.

Mots clés: Analyse de Cycle de Vie (ACV), impact environnemental, aquaculture, pêche, chalutage de fond, modèle écosystémique, Tunisie, Golfe de Gabès.

Environmental impact assessment of demersal trawling and aquaculture in Tunisia: comparative approach using Life Cycle Assessment (LCA)

The main goal of ecology is to place human activities within a framework of sustainable development by enhancing their economic benefits, their social attractiveness and their environmental performances. Ecosystems that support fisheries and aquaculture are subject to several alterations of significant relevance to their functioning and to their abilities to provide goods and services. Therefore, the long-term sustainability of fishing and aquaculture is a major concern from an environmental and ecological viewpoint. Both activities carry risks of negative environmental impacts because of its close relation with the immediate environment. To better understand environmental impacts and ensure the sustainability of fishing and aquaculture, it is necessary to develop an integrative science-based approach to impact assessment. Life Cycle Assessment (LCA) has emerged as a robust method to estimate potential environmental impacts associated with a product. It allows the assessment of environmental impacts "from cradle to grave", taking into account all stages of a product's life. This thesis focuses on the adaptation of LCA to demersal trawling and aquaculture in Tunisia. The goal is to explore how LCA improves the environmental evaluation of seafood production systems and how it helps to better understand their links with the environment. Results revealed that rearing practices and fish feed were the greatest contributors to the impacts studied due to the production of fish meal and oil and the low efficiency of feed use. The study also showed that impact intensity of demersal trawling was proportional to the amount of fuel consumed. LCA is a valuable tool for assessing how to improve environmental sustainability of demersal trawling and aquaculture.

Keywords: Life Cycle Assessment (LCA), Environmental impact, marine aquaculture, fisheries, demersal trawling, Tunisia, Gulf of Gabes.