Combining ecosystem indicators and life cycle assessment for environmental assessment of demersal trawling in Tunisia

Khaled Abdou, François Le Loc'h, Didier D. Gascuel, Mohamed Salah Romdhane, Joël Aubin, Frida Ben Rais Lasram

The International Journal of Life Cycle Assessment
https://doi.org/10.1007/s11367-019-01651-5

OCEAN RESOURCES & MARINE CONSERVATION

Combining ecosystem indicators and life cycle assessment for environmental assessment of demersal trawling in Tunisia

Khaled Abdou[1,2,3] · François Le Loc'h[3] · Didier Gascuel[4] · Mohamed Salah Romdhane[2] · Joël Aubin[5] · Frida Ben Rais Lasram[6]

Received: 23 August 2018 / Accepted: 16 June 2019

Abstract

Purpose The present study assesses environmental performance of seafood production by demersal trawling in Tunisia (Gulf of Gabes) in order to analyze the contribution of each production stage to environmental impacts and to understand drivers of the impacts using life cycle assessment (LCA). Then a set of 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.

Methods 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. Several ecosystem indicators from EwE were calculated. 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. Several management plans were simulated and their influence on environmental performance was assessed. 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.

Results and discussion LCA revealed that fuel consumption by fishing vessels, fuel production, and paint and antifouling production contributed most to environmental impacts. All management plans simulated decreased environmental impacts compared with 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.

Conclusions 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.

Responsible editor: Ian Vázquez-Rowe

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11367-019-01651-5) contains supplementary material, which is available to authorized users.

✉ Khaled Abdou
K.Abdou@cranfield.ac.uk

[1] School of Water, Energy and Environment, Cranfield University, College Road, Bedford MK43 0AL, UK

[2] UR 03AGRO1 Ecosystèmes et Ressources Aquatiques, Institut National Agronomique de Tunisie (INAT), Université de Carthage, 43 Avenue Charles Nicolle, 1082 Tunis, Tunisia

[3] UMR 6539 Laboratoire des Sciences de l'Environnement Marin (CNRS,UBO, IRD,Ifremer), Institut Universitaire Européen de la Mer (IUEM), Technopôle Brest Iroise, Rue Dumont d'Urville, 29280 Plouzané, France

[4] UMR 985 Ecologie et Santé des Ecosystèmes, Université Européenne de Bretagne, Agrocampus Ouest, 65 rue de Saint-Brieuc CS 84215, 35042 Rennes cedex, France

[5] UMR 1069, Sol Agro et hydrosystème Spatialisation, Institut National de la Recherche Agronomique (INRA), 65 rue de Saint Brieuc CS 84215, 35042 Rennes Cedex, France

[6] Univ. Littoral Côte d'Opale, Univ. Lille, CNRS, UMR 8187, LOG, Laboratoire d'Océanologie et de Géosciences, 62930 Wimereux, France

Published online: 02 July 2019

Keywords Life cycle assessment · Fisheries · Ecosystem modeling · Ecopath with Ecosim · Ecospace · Demersal trawling · Environmental impacts · Gulf of Gabes

1 Introduction

Seafood products represent more than 9% of the economic value of total agricultural exports and 1% of the 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). Fishing activity has expanded considerably in terms of fishing effort and the number of fishing units and fishing grounds, because of the increased demand and consumption of seafood and the technological development in fishing technologies, in addition to the fact that fisheries operate in an increasingly globalized environment (Pauly et al. 2002; Swartz et al. 2010). On a global scale, marine catches have remained relatively stagnant since 1996 (FAO 2016). Compared with 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). 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 a production or service, such as seafood production (Pelletier et al. 2007). Since the 2000s, LCA has been applied to fisheries and seafood production systems around the world (Ziegler et al. 2003, 2011; Hospido and Tyedmers 2005; Iribarren et al. 2010; Vázquez-Rowe et al. 2010, 2012a; Ramos et al. 2011; Fréon et al. 2014; Avadí et al. 2015; Abdou et al. 2017, 2018b). 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 2013), 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 2013). For example, a biotic resource use impact category was developed and applied to quantify the amount of biotic biomass removed by fishing activity (Boyd 2008; Driscoll et al. 2015; Langlois et al. 2014a; Parker and Tyedmers 2012a, b). 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). Nilsson and Ziegler (2007), Ramos et al. (2011), and Ziegler and Hansson (2003) applied seafloor area impact to different fisheries. The last 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. 2012b).

Ecosystem models are used in ecosystem-based fishery management to assess the sustainability, health, productivity, and resilience of ecosystems. This concept is used to incorporate ecosystem considerations for the sustainable utilization of marine resources and not just single-species management plans. 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. For instance, fuel consumption was found to be an important driver behind environmental impact of fisheries (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.

2 Materials and methods

2.1 Study area: the Gulf of Gabes

The Gulf of Gabes is located in southern Tunisia and in the southern Mediterranean Sea and it covers approximately 35,900 km^2 (Fig. 1). 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. 2015; 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). It is considered one of the most productive areas in the Mediterranean Sea in terms of catches (Halouani et al. 2015; 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 predominant fishing activity in the gulf (Hattab et al. 2013; Mosbah et al. 2013). Based on Tunisian Fisheries and Aquaculture Department (DGPA) statistics, the number of demersal trawlers increased to 285 from 1980 to 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); however, it is considered the most destructive fishing gear worldwide. Fuel consumption by demersal trawlers in the Gulf of Gabes varies between 35 and 180 metric tons of diesel per year, depending on trawler's size, number and length of fishing trips, main species targeted, and other technical

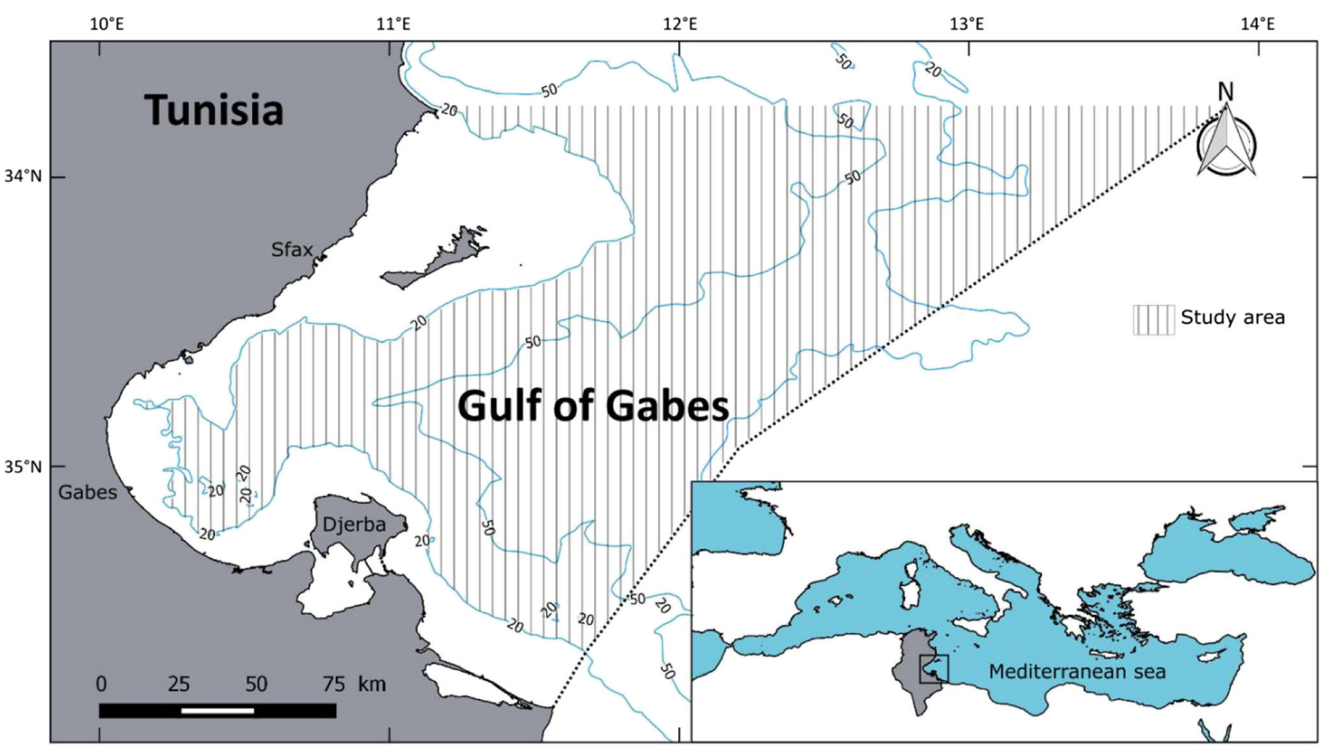

Fig. 1 Geographic location of the study area in the Gulf of Gabes ecosystem

characteristics. It damages bottom habitats and harms benthic communities, in addition to its non-selectivity (Kumar and Deepthi 2006). 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 (Hattab et al. 2013). Indeed, the 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. Therefore, it is necessary to establish adequate management practices to facilitate the recovery of marine resources. 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. 2018a; Hattab et al. 2013). Combining EwE with fish supply-chain models has been 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.

2.2 Life cycle assessment

The present study was based on a seafood LCA of demersal trawlers in Tunisia as case study (Abdou et al. 2018a) which quantified environmental impacts associated with landing seafood caught by wooden demersal trawlers in the Gulf of Gabes. It was performed following the four steps suggested by the International Reference Life Cycle Data System (European Commission 2010). The functional unit (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 because of the availability of reliable data for this group. The studied system covers a wide range of operational stages related to demersal trawling such as fuel consumption by fishing vessels, other inputs to fishing (reflecting onboard activities, release of paint and antifouling substances, etc.), fuel production, lubricating oil production, paint and antifouling paint production, trawler and trawl net construction and maintenance, and transport of materials upstream. 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 because those stages occur beyond the scope of fishery management decisions as examined in study. Although refrigerants have been shown to contribute heavily to certain environmental impact of fisheries, they were not included in this study because they are not used by any of the wooden demersal trawlers in Tunisia. Therefore, the LCA is considered as a “cradle-to-gate” because the final product is 1 t of seafood landed at the port gate. The main objective of the LCA was to analyze the contribution of each production stage to environmental impacts and to understand drivers of the impacts associated with demersal trawling. Thus, impacts were not allocated between coproducts.

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. Gathered data included trawlers’ operational aspects (e.g., fuel consumption, number of fishing trips, and number of days at sea) and information about vessel construction (e.g., material used for construction, paint and antifouling paint quantities, dimensions of vessels, life span). Collected data supplement and validate official statistics.

Mean lifespan of wooden vessels in the Gulf of Gabes is estimated at 40 years and maintenance and repair of vessels are taken into account by adding 25% of the total amount of wood used for vessel construction (Tyedmers 2000). The composition of paint and antifouling paint was obtained from material safety data sheets and validated by managers of the principal paint-producing company in Tunisia, and their emissions to water were estimated based on the assumption that two-thirds of the paint and antifouling paint used is released into the water (Hospido and Tyedmers 2005). Required background data were extracted from the ecoinvent 3.0 database (Weidema et al. 2013). See Abdou et al. (2018a) for further details about the method.

To estimate impacts, data were aggregated into 11 midpoint impact categories that reflect the environmental issues associated to fisheries and seafood production system. The selection was based on previous guidelines in fishery LCA studies (Avadí and Fréon 2013). Impacts were calculated per ton of seafood produced 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 to the atmosphere 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 potential contribution to radiative forcing via greenhouse gas emissions; 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 square meters per year (m^2 $year^{-1}$).
- 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 is found in Abdou et al. (2018a). All impact categories were calculated for an average demersal trawler in the Gulf of Gabes.

2.3 Ecopath with Ecosim modeling

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 to provide a complete assessment of trawling's environmental impacts and place its results in an ecosystem context:

Pressure indicators

- PPR: represents the primary production required to sustain the catches and the consumption by the trophic groups. 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: $PPR = \sum_{paths}\left[Y.\prod_{pred,prey}\frac{Q_{pred}}{P_{pred}}.DC'_{pred,prey}\right]$, 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): $PR = \sum_{i=1}^{n}\frac{Y_i}{CR}.\left(\frac{1}{TE}\right)^{(TL_i-1)}$, 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, and the values expressed using EwE are different than those reported in other LCA studies because of the difference in calculation methods and the units. 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.

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).

The Ecosim approach was used to carry out dynamic simulation using the parameters from the balanced Ecopath model. Landing data, time series of fishing effort by fishing gear, and stock assessment estimates were collected by the Tunisian National Institute of Sciences and Technologies of the Sea. Ecosim was fitted to landings for the period 1995–2008. 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. Each cell represents land or water and is assigned to a specific habitat type (nine habitat types were included). Each of the 41 functional groups was assigned to its preferred habitat (i.e., where the feeding rate was high, based on the available information on the ecology and biology of each species and expert advice), and each fishery fleet was assigned to the fishing zones authorized by Tunisian fisheries regulations. The modeled area extended from the 20-m contour depth to approximately the 200-m isobaths, because of lack of reliable data. 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).

2.3.1 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) and do not reflect desired or planned management plans, but rather represent contrasting scenarios for the spatial and temporal management plans. Scenarios consisted of implementing temporal and spatial measures to explore potential ecosystem response (Fig. 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)

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). Then, the new catch and biomass values (after a 15-year run) predicted from the Ecopsace model were used to re-estimate the different environmental impacts (using LCA) and recalculate the ecosystem indicators. All results were then compared with 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.

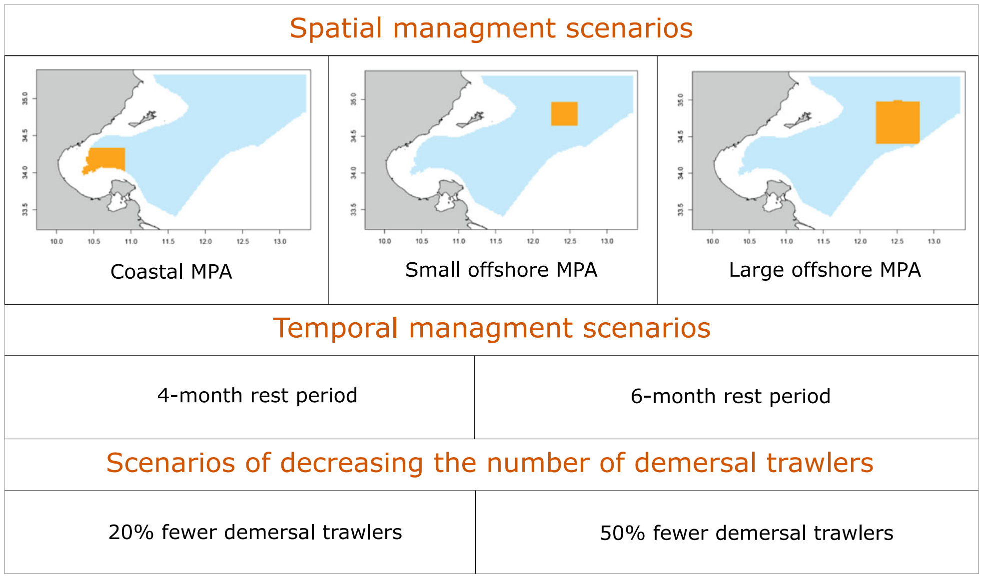

Fig. 2 Demersal trawling management plans in the Gulf of Gabes simulated with the Ecospace model. MPA = marine protected area. Orange represents the MPA, blue is the area included in the model and gray represents land

3 Results

3.1 LCA results for the current situation

Estimated environmental impacts of an average demersal trawler under the current situation are presented in Table 1. Fuel production is responsible for around 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}). Fuel consumption by fishing vessels is the largest contributor to acidification (84% of 155.8 kg SO_2 eq t^{-1}), global warming (81% of 13,773 kg CO2 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 of materials upstream does not contribute greatly to impacts (Table 1).

3.2 EwE indicators of the current situation

The pressure indicators reveal a PPR of yield of 240.6 kg of wet weight km^{-2} (126.9 and 113.8 kg of wet weight 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 kg of wet weight km^{-2} 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 resource 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% (Table 2).

3.3 Scenario results

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 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%) (Table 2).

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 with 59% in the baseline scenario (Fig. 3). Total PPR increases to 305.64 kg of wet weight km^{-2}, which is a 27% increase compared with 31% in the baseline scenario; however, PPR of demersal trawlers decreases as much as in the baseline scenario (44%). Total PPR/catch

Table 1 Contribution of operational stages to mean environmental impacts per ton 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

	Fuel consumption by fishing vessels	Other inputs to fishing	Fuel production	Lubricating oil production	Paint and antifouling production	Trawler and net construction	Transport of materials upstream	Total
ADP (kg Sb eq)	0	0	89.815	0.446	0.553	3.052	0.037	93.902
%	0	0	95.648	0.475	0.588	3.250	0.039	100
AP (kg SO_2 eq)	130.093	0.368	21.816	0.157	0.942	2.398	0.038	155.813
%	83.493	0.236	14.002	0.101	0.605	1.539	0.024	100
EP (kg PO_4 eq)	5.307	0.021	3.050	0.028	0.468	0.443	0.003	9.320
%	56.943	0.225	32.735	0.296	5.016	4.753	0.032	100
GWP (kg CO_2 eq)	11,154.500	2.450	2097.514	18.923	61.390	433.472	5.085	13,773.340
%	80.987	0.017	15.229	0.137	0.446	3.147	0.037	100
ODP (kg CFC-11)	0	0	0.002	0.000	0	0	0	0.003
%	0	0	96.969	0.302	0.567	2.125	0.037	100
POFP (kg C_2H_4 eq)	0.868	0.001	1.284	0.006	0.059	0.138	0.001	2.358
%	36.812	0.042	54.485	0.240	2.521	5.844	0.056	100
HTP (kg 1,4-DCB eq)	302.271	1.263	1181.476	6.812	283.388	2316.530	3.028	4094.770
%	7.381	0.031	28.853	0.166	6.921	56.573	0.074	100
METP (kg 1,4-DCB eq)	0	0.001	88,3195.798	6359.253	215,540.87	477,733.42	1113.128	1,583,942.50
%	0	0	55.759	0.401	13.608	30.161	0.07	100
TETP (kg 1,4-DCB eq)	0	0	12.716	0.092	1.329	74.658	0.019	88.814
%	0	0	14.318	0.103	1.496	84.061	0.022	100
LOP (m^2 year)	0	0	67.455	0.335	14.822	36.285	0.309	119.206
%	0	0	56.586	0.281	12.434	30.439	0.26	100
TCED (MJ)	0	0	203,568.127	1010.632	1355.03	6619.68	83.679	212,637.140
%	0	0	95.735	0.475	0.637	3.113	0.0393	100

increases by 102%, compared with a 100% increase in the baseline scenario. PPR/catch of demersal trawlers decreases by 1.6% compared with 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 with 3.8, and the API increases to reach 50% instead of 44% (Fig. 4).

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 with 59% in the baseline scenario (Fig. 3). 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) (Fig. 4).

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 (Fig. 3), which is better than the 59% increase in impacts in the

Table 2 Mean Ecospace indicator results and environmental impacts per ton 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	13,773.3	21,930.8	+ 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	4094.7	6519.9	+ 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^2 year	119.2	189.8	+ 59.2%
Total cumulative energy demand	MJ	212,637.1	338,574.7	+ 59.2%
Primary production required (PPR)	kg of wet weight 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 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%

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% (Fig. 4).

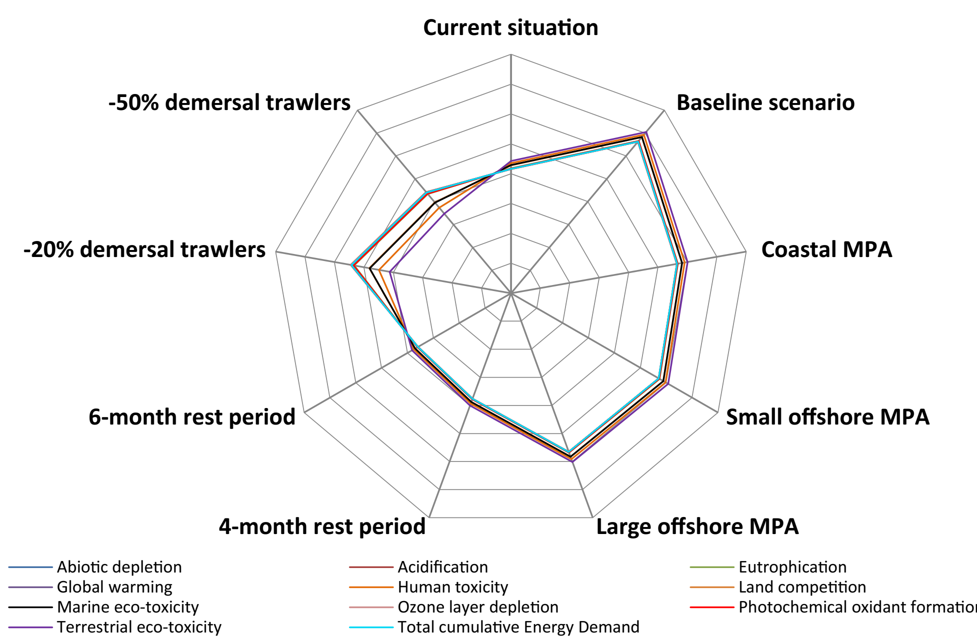

Fig. 3 Environmental impacts per t of seafood produced by an average demersal trawler in the Gulf of Gabes in the current situation and under eight 15-year scenarios. The levels represent the relative environmental impacts

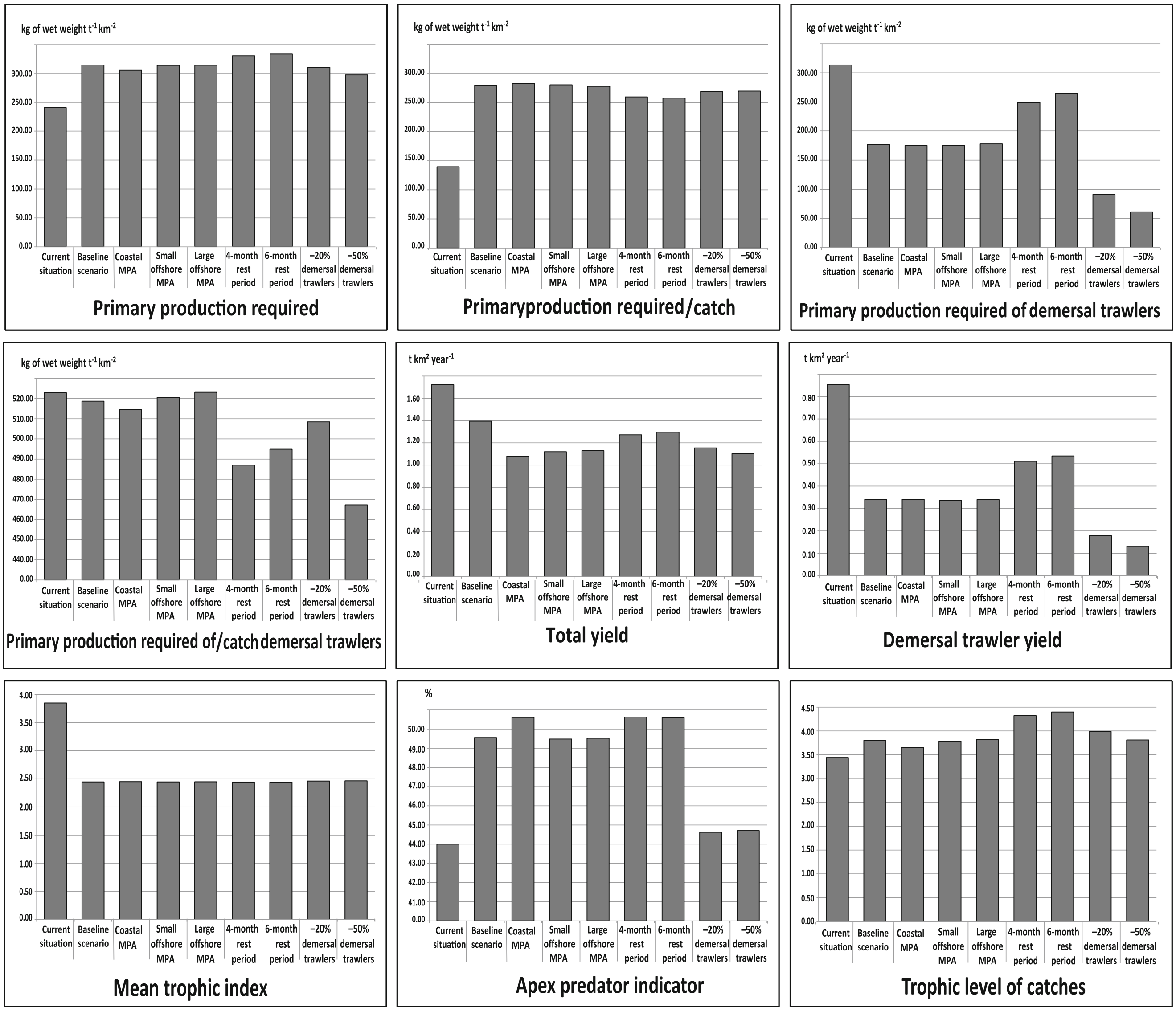

Fig. 4 Ecospace indicator results in the Gulf of Gabes under the current situation and eight 15-year scenarios

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 when 20% of demersal trawlers are eliminated, abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion, photochemical oxidant formation, and total cumulative energy demand decrease by approximately 31% compared with the baseline scenario. On the other hand, a 50% reduction in demersal trawler number results in the decrease of those impact categories by 55% compared with the baseline scenario. Marine aquatic ecotoxicity and land occupation decrease by 46% and 66% compared with the baseline scenario, when eliminating 20% and 50% of demersal trawlers, respectively. Human toxicity decreases by 56% compared with the baseline case when 20% of demersal trawlers were eliminated and decreases by 73% compared with the baseline scenario when 50% of demersal trawlers were eliminated. Terrestrial ecotoxicity decreases by 66% and 81% compared with the baseline scenario when 20% or 50% of demersal trawlers were eliminated, respectively (Fig. 3).

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 (Fig. 4).

4 Discussion

LCA impacts calculated for 1 t of landed seafood showed that fuel production and fuel consumption by fishing vessels 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 2013; Schau et al. 2009). Avadí and Fréon (2013) stated that fuel combustion and production contributes most to environmental impacts of fishing vessels, and several fishery LCAs demonstrated that fuel consumption 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. 2012a). Demersal trawlers in the Gulf of Gabes consume 4841 l of diesel to produce one metric ton of seafood, which is twice the global average for bottom trawl fisheries (around 2000 l per metric ton of seafood) estimated by Parker and Tyedmers (2015) and almost 10 times higher than the global average for fisheries (489 l of diesel per metric ton of seafood) estimated by Parker et al. (2018). 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 2013). 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. This can be explained by the fact that only wooden vessels were considered in this study while most other fishery LCA studies considered vessels with steel hull. 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 of materials upstream contributes much less to impacts than to the other processes, which suggests that it is not a key subsystem of demersal trawling in the Gulf of Gabes.

Although LCA provides 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 to 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. 1994), *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 (high MTI and TLc). This finding is in line with what was found in Hattab et al. (2013). LCA results demonstrated that demersal trawling in the gulf has high environmental impacts in all categories. This finding was supported by a comparison with other fishery LCA studies in Abdou et al. (2018a). 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 with 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). 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 with 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 with 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 and establish a "cradle-to-grave" LCA instead of just a "cradle-to-gate" LCA. 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 with data reliability and the complexity of the ecosystem.

Table 3 Changes in impact categories and ecosystem indicators compared with 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

5 Conclusions

This study developed a framework to supplement the LCA of seafood production with ecosystem indicators from Ecopath with Ecosim. 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 fuel consumption by fishing vessels, fuel production, and paint and antifouling production were the main contributors to environmental impacts. 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 with 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 with those of the baseline scenario. Total primary production required of demersal trawlers increased in this scenario, but PPR/catch of demersal trawlers greatly decreased. Apex predator index and trophic level of catch 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.

Funding information The authors would like to acknowledge valuable financial support from the "Institut de Recherche pour le Développement" (JEAI GAMBAS project). This study was partially funded by the "ICV pêche" project and the "LabexMer" (ANR-10-LABX-19).

References

Abdou K, Halouani G, Hattab T, Romdhane MS, Ben Rais Lasram F, Le Loc'h F (2016) Exploring the potential effects of marine protected areas on the ecosystem structure of the Gulf of Gabes using the Ecospace model. Aquat Living Resour 29:202. https://doi.org/10.1051/alr/2016014

Abdou K, Aubin J, Romdhane MS, Le Loc'h F, Ben Rais Lasram F (2017) Environmental assessment of seabass (*Dicentrarchus labrax*) and seabream (*Sparus aurata*) farming from a life cycle perspective: a case study of a Tunisian aquaculture farm. Aquaculture 471:204–212. https://doi.org/10.1016/j.aquaculture.2017.01.019

Abdou K, Gascuel D, Aubin J, Romdhane MS, Ben Rais Lasram F, Le Loc'h F (2018a) Environmental life cycle assessment of seafood production: a case study of trawler catches in Tunisia. Sci Total Environ 610-611:298–307. https://doi.org/10.1016/j.scitotenv.2017.08.067

Abdou K, Ben Rais Lasram F, Romdhane MS, Le Loc'h F, Aubin J (2018b) Rearing performances and environmental assessment of sea cage farming in Tunisia using life cycle assessment (LCA) combined with PCA and HCPC. Int J Life Cycle Assess 23:1049–1062

Avadí A, Fréon P (2013) Life cycle assessment of fisheries: a review for fisheries scientists and managers. Fish Res 143:21–38. https://doi.org/10.1016/j.fishres.2013.01.006

Avadí A, Fréon P, Tam J (2014) Coupled ecosystem/supply chain modelling of fish products from sea to shelf: the Peruvian anchoveta case. PLoS One 9:e102057. https://doi.org/10.1371/journal.pone.0102057

Avadí A, Bolaños C, Sandoval I, Ycaza C (2015) Life cycle assessment of Ecuadorian processed tuna. Int J Life Cycle Assess 20:1415–1428. https://doi.org/10.1007/s11367-015-0943-2

Batisse M, Jeudy de Grissac A (1998) A global representative system of marine protected areas. Mar. Reg. 3 Mediterr. World Bank Int. Union Conserv Nat Nat Resour 1:87

Ben Meriem S, Gharbi H, Ezzeddine-Najai S (1994) Le rouget de roche (*Mullus surmuletus*) en Tunisie: évaluation des stocks et aménagement des pêcheries. Cons. Général Pêch. Pour Méditerranée Consult Techn Éval. Stocks Tunis Tunis, pp 8–12

Ben Rais Lasram F, Hattab T, Halouani G, Romdhane M, Le Loc'h F, Albouy C (2015) Cumulative human threats on fish biodiversity components in Tunisian waters. Mediterr Mar Sci 17:190. https://doi.org/10.12681/mms.1373

Bourdaud P, Gascuel D, Bentorcha A, Brin d'Amour A (2016) New trophic indicators and target values for an ecosystem-based management of fisheries. Ecol Indic 61:588–601. https://doi.org/10.1016/j.ecolind.2015.10.010

Boyd C (2008) From ocean to market: the life cycle biophysical impacts of the southwest Nova Scotia live lobster industry. Masters thesis. Dalhousie University, Halifax

Christensen V, Walters CJ (2004) Ecopath with Ecosim: methods, capabilities and limitations. Ecol Model 172:109–139. https://doi.org/10.1016/j.ecolmodel.2003.09.003

Christensen V, Guenette S, Heymans JJ, Walters CJ, Watson R, Zeller D, Pauly D (2003) Hundred-year decline of North Atlantic predatory fishes. Fish Fish 4:1–24

Christensen V, Walters C, Pauly D, Forrest R (2008) Ecopath with Ecosim version 6 user guide. Lenfest Ocean Futures Project, University of British Columbia, Vancouver

Coll M, Palomera I, Tudela S, Sardà F (2006) Trophic flows, ecosystem structure and fishing impacts in the south Catalan Sea, northwestern Mediterranean. J Mar Syst 59:63–96

Costello C, Ovando D, Clavelle T, Strauss CK, Hilborn R, Melnychuk MC, Branch TA, Gaines SD, Szuwalski CS, Cabral RB, Rader DN, Leland A (2016) Global fishery prospects under contrasting management regimes. Proc Natl Acad Sci 113:512–5129

DGPA (2015) AnnuairedesstatistiquesdespêchesenTunisie. Ministèredel'Agriculture, Tunisie

Dhieb K, Ghorbel M, Jarboui O, Bouaïn A (2007) Exploitation status and stock assessment by pseudo-cohort analysis of the bluefish, Pomatomus saltatrix, in the Gulf of Gabes (Tunisia). J Mar Biol Assoc UK 87:1315–1319

Driscoll J, Boyd C, Tyedmers P (2015) Life cycle assessment of the Maine and southwest Nova Scotia lobster industries. Fish Res 172:385–400

Emanuelsson A, Ziegler F, Pihl L, Sköld M, Sonesson U (2014) Accounting for overfishing in life cycle assessment: new impact

categories for biotic resource use. Int J Life Cycle Assess 19:1156–1168. https://doi.org/10.1007/s11367-013-0684-z
European Commission (2010) International Reference Life Cycle Data System (ILCD) Handbook -General guide for Life Cycle Assessment. Joint Research Centre. Institute for Environment and Sustainability, Luxembourg
FAO (2016) The state of world fisheries and aquaculture: contributing to food security and nutrition for all. Food and Agriculture Organization of the United Nations, Rome
Fiorentino F, Ben Meriem S, Bahri T, Camilleri M, Dimech M, Ezzeddine-Naja S, Massa F, Jarbaoui O, Zgozi S (2008) Synthesis of information on some target species in the MedSudMed project area (Central Mediterranean). Med Sud Med Tech Doc 15:67
Fréon P, Avadí A, Vinatea Chavez RA, Iriarte Ahón F (2014) Life cycle assessment of the Peruvian industrial anchoveta fleet: boundary setting in life cycle inventory analyses of complex and plural means of production. Int J Life Cycle Assess 19:1068–1086. https://doi.org/10.1007/s11367-014-0716-3
Gharbi H, Ben Meriem S, Bedoui R, El Abed A (2004) Les pêcheries tunisiennes du rouget de vase (Mullus barbatus Linnaeus, 1758): évaluation des stocks et aménagement des pêcheries. Mar Life 14: 49–57
Glass CW (2000) Conservation of fish stocks through bycatch reduction: a review. Northeast Nat 7:395–410
Goedkoop M, De Schryver A, Oele M, Durksz S, de Roest D (2008) Introduction to LCA with SimaPro 7. Pré-Consultants, Amersfoort
Guizien K, Belharet M, Marsaleix P, Guarini JM (2012) Using larval dispersal simulations for marine protected area design: application to the Gulf of Lions (northwest Mediterranean). Limnol Oceanogr 57:1099–1112. https://doi.org/10.4319/lo.2012.57.4.1099
Guyonnet B, Grall J, Vincent B (2008) Modified otter trawl legs to reduce damage and mortality of benthic organisms in North East Atlantic fisheries (Bay of Biscay). J Mar Syst 72:2–16
Halouani G, Hattab T, Ben Rais Lasram F, Romdhane MS, Le Loc'h F (2013) A trophodynamic approach for the evaluation of fishery management plans in the gulf of Gabes (southern Tunisia). Rapp Comm Int Mer Médit 40:756
Halouani G, Gascuel D, Hattab T, Ben Rais Lasram F, Coll M, Tsagarakis K, Piroddi C, Romdhane MS, Le Loc'h F (2015) Fishing impact in Mediterranean ecosystems: an EcoTroph modeling approach. J Mar Syst 150:22–33. https://doi.org/10.1016/j.jmarsys.2015.05.007
Halouani G, Abdou K, Hattab T, Romdhane MS, Ben Rais Lasram F, Le Loc'h F (2016) A spatio-temporal ecosystem model to simulate fishing management plans: a case of study in the Gulf of Gabes (Tunisia). Mar Policy 69:62–72. https://doi.org/10.1016/j.marpol.2016.04.002
Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'Agrosa C, Bruno JF, Casey KS, Ebert C, Fox HE, Fujita R, Heinemann D, Lenihan HS, Madin EMP, Perry MT, Selig ER, Spalding M, Steneck R, Watson R (2008) A global map of human impact on marine ecosystems. Science 319:948–952. https://doi.org/10.1126/science.1149345
Hattab T, Ben Rais Lasram F, Albouy C, Romdhane MS, Jarboui O, Halouani G, Cury P, Le Loc'h F (2013) An ecosystem model of an exploited southern Mediterranean shelf region (Gulf of Gabes, Tunisia) and a comparison with other Mediterranean ecosystem model properties. J Mar Syst 128:159–174. https://doi.org/10.1016/j.jmarsys.2013.04.017
Hattour A (1991) Le chalutage dans les eaux Tunisiennes réalités et considérations législatives particulièrement dans les Golfe de Tunis et de Gabès. Note Inst. Natl. Sci. Tech. Océan. Pêche Salammbô
Hayman B, Dogliani M, Kvale I, Fet AM (2000) Technologies for reduced environmental impact from ships-ship building, maintenance and dismantling aspects. ENSUS-2000 Newctle. Tyne UK
Hospido A, Tyedmers P (2005) Life cycle environmental impacts of Spanish tuna fisheries. Fish Res 76:174–186. https://doi.org/10.1016/j.fishres.2005.05.016
Iribarren D, Vázquez-Rowe I, Hospido A, Moreira MT, Feijoo G (2010) Estimation of the carbon footprint of the Galician fishing activity (NW Spain). Sci Total Environ 408:5284–5294. https://doi.org/10.1016/j.scitotenv.2010.07.082
Jackson JB, Kirby MX, Berger WH, Bjorndal KA, Botsford LW, Bourque BJ, Bradbury RH, Cooke R, Erlandson J, Estes JA, Hughes TP, Kidwell S, Lange CB, Lenihan HS, Pandolfi JM, Peterson CH, Steneck RS, Tegner MJ, Warner RR (2001) Historical overfishing and the recent collapse of coastal ecosystems. Science 293:629–637
Jarboui O, Ghorbel M, Bouaïn A (1998) Le stock du pageot (Pagellus erythrinus) dans le golfe de Gabès (Tunisie): etat d'exploitation et possibilités d'aménagement. Cah Options Méditerranéennes 35: 251–260
Kaiser MJ, De Groot SJ (2000) Effects of Fishing on non-target species and habitats. Biological, conservation socio-economic issues. Blackwell Science, Oxford
Kaiser M, Clarke K, Hinz H, Austen M, Somerfield P, Karakassis I (2006) Global analysis of response and recovery of benthic biota to fishing. Mar Ecol Prog Ser 311:1–14
Kumar AB, Deepthi G (2006) Trawling and by-catch: implications on marine ecosystem. Curr Sci 90:922–931
Lamon L, Rizzi J, Bonaduce A, Dubois C, Lazzari P, Ghenim L, Gana S, Somot S, Li L, Canu DM, Solidoro C, Pinardi N, Marcomini A (2014) An ensemble of models for identifying climate change scenarios in the Gulf of Gabes, Tunisia. Reg Environ Chang 14:31–40
Langlois J, Fréon P, Delgenes J-P, Steyer J-P, Hélias A (2014a) New methods for impact assessment of biotic-resource depletion in life cycle assessment of fisheries: theory and application. J Clean Prod 73:63–71. https://doi.org/10.1016/j.jclepro.2014.01.087
Langlois J, Fréon P, Steyer J-P, Delgenès J-P, Hélias A (2014b) Sea-use impact category in life cycle assessment: state of the art and perspectives. Int J Life Cycle Assess 19:994–1006. https://doi.org/10.1007/s11367-014-0700-y
Libralato S, Coll M, Tudela S, Palomera I, Pranovi F (2008) Novel index for quantification of ecosystem effects of fishing as removal of secondary production. Mar Ecol Prog Ser 355:107–129
Luong AD, Schaubroeck T, Dewulf J, De Laender F (2015) Re-evaluating primary biotic resource use for marine biomass production: a new calculation framework. Environ Sci Technol 49:11586–11593. https://doi.org/10.1021/acs.est.5b02515
Missaoui H, Jabeur C, Gobert R, Jarboui O, El Abed A (2000) Analyse typologique de la flottille chalutière du golfe de Gabès, Sud-Est de Tunisie. Bull Inst Natn Scien Tech Mer Salammbô 27:15–26
Mosbah S, Verdoit-Jarraya M, Ghorbel M, Jarboui O, Lenfant P (2013) Modelling temporal evolution of the production from coastal fishery and bottom trawling during one decade (1995–2006) in the gulf of Gabes (Tunisia). Available from: http://ciesm.org/online/archives/abstracts/pdf/40/PG_0760.pdf (accessed 17 February 2017)
Natale S, Sorgente R, Ribotti A, Olita A et al (2006) Central Mediterranean Sea forecast: effects of high-resolution atmospheric forcings. Ocean Sci Discuss 3:637–669
Nilsson P, Ziegler F (2007) Spatial distribution of fishing effort in relation to seafloor habitats in the Kattegat, a GIS analysis. Aquat Conserv Mar Freshw Ecosyst 17:421–440
Papaconstantinou C, Farrugio H (2000) Fisheries in the Mediterranean. Mediterr Mar Sci 1:5–18
Parker RW, Tyedmers PH (2012a) Life cycle environmental impacts of three products derived from wild-caught Antarctic krill (Euphausia superba). Environ Sci Technol 46:4958–4965
Parker RW, Tyedmers PH (2012b) Uncertainty and natural variability in the ecological footprint of fisheries: a case study of reduction fisheries for meal and oil. Ecol Indic 16:76–83

Parker RW, Tyedmers PH (2015) Fuel consumption of global fishing fleets: current understanding and knowledge gaps. Fish Fish 16: 684–696

Parker RW, Blanchard JL, Gardner C, Green BS, Hartmann K, Tyedmers PH, Watson RA (2018) Fuel use and greenhouse gas emissions of world fisheries. Nat Clim Chang 8:333

Pauly D, Christensen V (1995) Primary production required to sustain global fisheries. Nature 374:255–257

Pauly D, Watson R (2005) Background and interpretation of the 'marine trophic index'as a measure of biodiversity. Philos Trans R Soc Lond Ser B Biol Sci 360:415–423

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

Pauly D, Christensen V, Guénette S, Pitcher TJ, Sumaila UR, Walters CJ, Watson R, Zeller D (2002) Towards sustainability in world fisheries. Nature 418:689–695

Pelletier NL, Ayer NW, Tyedmers PH, Kruse SA, Flysjo A, Robillard G, Ziegler F, Scholz AJ, Sonesson U (2007) Impact categories for life cycle assessment research of seafood production systems: review and prospectus. Int J Life Cycle Assess 12:414–421. https://doi.org/10.1065/lca2006.09.275

Plagányi ÉE (2007) Models for an ecosystem approach to fisheries. Food and Agriculture Organization of the United Nations, Rome

Ramos S, Vázquez-Rowe I, Artetxe I, Moreira MT, Feijoo G, Zufía J (2011) Environmental assessment of the Atlantic mackerel (Scomber scombrus) season in the Basque Country. Increasing the timeline delimitation in fishery LCA studies. Int J Life Cycle Assess 16:599–610. https://doi.org/10.1007/s11367-011-0304-8

Sammari C, Koutitonsky VG, Moussa M (2006) Sea level variability and tidal resonance in the Gulf of Gabes, Tunisia. Cont Shelf Res 26: 338–350. https://doi.org/10.1016/j.csr.2005.11.006

Schau EM, Ellingsen H, Endal A, Aanondsen SA (2009) Energy consumption in the Norwegian fisheries. J Clean Prod 17:325–334

Svanes E, Vold M, Hanssen OJ (2011) Environmental assessment of cod (Gadus morhua) from autoline fisheries. Int J Life Cycle Assess 16: 611–624. https://doi.org/10.1007/s11367-011-0298-2

Swartz W, Sala E, Tracey S, Watson R, Pauly D (2010) The spatial expansion and ecological footprint of fisheries (1950 to present). PLoS One 5:e15143

Thrane M (2004) Energy consumption in the Danish fishery: identification of key factors. J Ind Ecol 8:223–239

Tremblay-Boyer L, Gascuel D, Watson R, Christensen V, Pauly D (2011) Modelling the effects of fishing on the biomass of the world's oceans from 1950 to 2006. Mar Ecol Prog Ser 442:169–185

Tyedmers PH (2000) Salmon and sustainability: the biophysical cost of producing salmon through the commercial salmon fishery and the intensive salmon culture industry (PhD thesis). The University of British Columbia

Tyedmers PH, Watson R, Pauly D (2005) Fueling global fishing fleets. AMBIO J Hum Environ 34:635–638

Ulanowicz RE, (1995) Ecosystem Trophic Foundations: Lindeman Exonerata. In: Chapter 21 p. 549-560 In: B.C. Patten and S.E. Jørgensen (eds.) Complex ecology: the part-whole relation in ecosystems, Englewood Cliffs, Prentice Hall.

Vázquez-Rowe I, Moreira MT, Feijoo G (2010) Life cycle assessment of horse mackerel fisheries in Galicia (NW Spain): comparative analysis of two major fishing methods. Fish Res 106:517–527. https://doi.org/10.1016/j.fishres.2010.09.027

Vázquez-Rowe I, Moreira MT, Feijoo G (2012a) Environmental assessment of frozen common octopus (Octopus vulgaris) captured by Spanish fishing vessels in the Mauritanian EEZ. Mar Policy 36: 180–188. https://doi.org/10.1016/j.marpol.2011.05.002

Vázquez-Rowe I, Moreira MT, Feijoo G (2012b) Inclusion of discard assessment indicators in fisheries life cycle assessment studies. Expanding the use of fishery-specific impact categories. Int J Life Cycle Assess 17:535–549. https://doi.org/10.1007/s11367-012-0395-x

Walters C, Christensen V, Pauly D (1997) Structuring dynamic models of exploited ecosystems from trophic mass-balance assessments. Rev Fish Biol Fish 7:139–172

Walters C, Pauly D, Christensen V (1999) Ecospace: prediction of mesoscale spatial patterns in trophic relationships of exploited ecosystems, with emphasis on the impacts of marine protected areas. Ecosystems 2:539–554

Weidema BP, Bauer C, Hischier R, Mutel C, Nemecek T, Reinhard J, Vadenbo C, Wernet G (2013) Overview and methodology: data quality guideline for the ecoinvent database version 3. Swiss Centre for Life Cycle Inventories

World Bank (2017) The sunken billions revisited: progress and challenges in global marine fisheries. World Bank. Environment and Sustainable Development series, Washington, DC

Worm B, Hilborn R, Baum JK, Branch TA, Collie JS, Costello C, Fogarty MJ, Fulton EA, Hutchings JA, Jennings S, Jensen OP, Lotze HK, Mace PM, McClanahan TR, Minto C, Palumbi SR, Parma AM, Ricard D, Rosenberg AA, Watson R, Zeller D (2009) Rebuilding global fisheries. Science 325:578–585

Ziegler F, Hansson P-A (2003) Emissions from fuel combustion in Swedish cod fishery. J Clean Prod 11:303–314

Ziegler F, Nilsson P, Mattsson B, Walther Y (2003) Life cycle assessment of frozen cod fillets including fishery-specific environmental impacts. Int J Life Cycle Assess 8:39–47

Ziegler F, Emanuelsson A, Eichelsheim JL, Flysjö A, Ndiaye V, Thrane M (2011) Extended life cycle assessment of southern pink shrimp products originating in Senegalese artisanal and industrial fisheries for export to Europe. J Ind Ecol 15:527–538. https://doi.org/10.1111/j.1530-9290.2011.00344.x