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Original Article

Shaping sustainability of seafood from capture fisheries integrating the perspectives of supply chain stakeholders through combining systems analysis tools

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Seafood from capture fisheries can be assessed in many ways and for different purposes, with sometimes divergent views on what characterizes "sustainable use". Here we use two systems analysis tools Ecological Risk Assessment for Effects of Fishing (ERAEF) and Life Cycle Assessment (LCA) over the historical development of the Australian Patagonian toothfish fishery at Heard and McDonald Islands since the start in 1997. We find that ecological risks have been systematically identified in the management process using ERAEF, and with time have been mitigated, resulting in a lower risk fishery from an ecological impact perspective. LCA inventory data from the industry shows that fuel use per kilo has increased over the history of the fishery. Our results suggest that LCA and ERAEF may provide contrasting and complementary perspectives on sustainability and reveal trade-offs when used in combination. Incorporation of LCA perspectives in assessing impacts of fishing may facilitate refinement of ecosystem-based fisheries management, such as improved integration of the different perspectives of supply chain stakeholders.

Keywords: *Dissostichus eleginoides*, ecological risk assessment, fisheries, fuel, Life Cycle Assessment, sustainable seafood products

Introduction

In a globalized world with increasing pressures from human ac tivities (Steffen *et al.*, 2015), it has been argued that there is a need for improved recognition of off site impacts in ecosystem assessments through use of systems analysis tools, such as Life Cycle Assessment (LCA) and Ecological Risk Assessment (ERA) frameworks (Pascual *et al.*, 2017). For seafood production from capture fisheries, these tools differ in their scope, focus, and ap plication. One widely used ERA example is the Ecological Risk Assessment for the Effects of Fishing (ERAEF), a place based management tool to address the ecological risks of fishing (Hobday *et al.*, 2011). This risk based approach is extensively used in management of Commonwealth fisheries in Australia and elsewhere, and has contributed to ecosystem based fisheries man agement (EBFM; Scandol *et al.*, 2005). The method allows identi fication of relative risks from a variety of fishing associated activities across a suite of species, habitats, and ecological com munities. When linked to management actions, ERAEF outcomes can affect the operation of the industry and potentially the envi ronmental profile of the seafood product. LCA picks up where

ERAEF ends; it is a product oriented approach, quantitatively assessing broad environmental pressures from products using a systems perspective (Ness *et al.*, 2007). LCA quantifies the "footprint" of seafood products (i.e. product performance) along the supply chain through a set of methods assessing (mainly) resource use and emission based pressures, including, for example, global warming potential and energy use. ERA and LCA can thus be seen as complementary tools.

Although LCA results have repeatedly shown that management actions in a fishery have a strong influence on the environmental performance of seafood products (Ziegler *et al.*, 2016), LCA has to date only been applied in an industry and research context, without direct uptake in fishery management systems. To some extent, this may be an effect of a lack of robust methods in LCA for addressing ecological pressures from fisheries the central area of responsibility of agencies managing fisheries. With increased consumer and supplier interest in sustainability, seen for example in the rise of seafood certification and the influence of consumer guides (FAO, 2016; Ziegler *et al.*, 2016b), it is important to (i) properly address both off site and local effects of global supply chains and (ii) continue shaping approaches to seafood product sustainability for future food security. Important seafood certification schemes, such as the Marine Stewardship Council (MSC), make direct use of ecological risk assessment methods based on ERAEF, but MSC does not include fuel use, greenhouse gas emissions (GHG), or other supply chain indicators, such as utilization of catch in their certification criteria (Ziegler *et al.*, 2016a). The objective of this study is to combine results from ERAEF (on ecological risks) and LCA (on fuel use) for a case study fishery, to investigate potential uses in a seafood context.

The case study fishery is the Australian fishery for Patagonian toothfish (*Dissostichus eleginoides*) at the Heard Island and McDonald Island (HIMI). This is, to our knowledge, one of the two fisheries in the world with both ERAEF informing management and for which initial LCAs have been undertaken by one of the two operating fishing companies (holding over 70% of the access rights) as part of a voluntary initiative to offset their GHGs, and also the first seafood industry initiative in the world in this sense. The other fishery to have both ERAEF and parts of its industry undertake an LCA is the prawn fishery in northern Australia, where the same fishing company also operates (AFMA, 2018; Austral Fisheries, 2017). Consequently, the fishery at HIMI has data available for both ERAEF and LCA, including data over the entire history of commercial exploitation of the fishery (commercial fishing began in 1997). This allows studying the ecological risks and fuel use during the transition from a new to an established fishery and may reveal synergies and potential trade offs relevant to EBFM.

A quantitative and objective environmental assessment of toothfish as a seafood product, using both LCA and ERAEF, may also be useful to address key concerns of different stakeholders in the supply chain, such as various ecological risks or GHG emissions. Fisheries for toothfish (comprising two species, Patagonian and Antarctic toothfish *Dissostichus mawsoni*, and several stocks) have received substantial negative attention related to previously widespread illegal fishing (Osterblom *et al.*, 2015) and general environmental concern about targeting a long lived, deep water fish in the pristine waters of the Antarctic (e.g. Griffiths, 2010; Croxall and Nicol, 2004). During the history of exploitation, a range of management and conservation measures have been enforced and the global market now comprises products from several sub fisheries: over half of the global product volume, including the HIMI fishery, is certified by the MSC (MSC, 2017) and is today thus marketed to consumers as "sustainable seafood" and recommended by seafood consumer guides, while the remaining volume is not certified and is often categorized by consumer guides as "avoid". Eco labels and consumer guides have also been subject to criticism regarding their toothfish certification (e.g. Ward, 2008; Jacquet *et al.*, 2010; Christian *et al.*, 2013; or just Google toothfish + "Marine Stewardship Council"), resulting in contradictory market signals ("Is toothfish a good choice of fish or not?"). The specific aim of this study is thus to examine the influence of management measures and industry initiatives on seafood sustainability indicators based on both ERAEF and LCA over time. Based on these results, we then discuss opportunities and caveats for future assessment, reporting and improvement to manage both local and global pressures of fisheries.

Material and methods

The case study fishery

The fishery takes place in an area managed with an ecosystem based approach under the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR), division 58.5.2. This has resulted in a need to meet a range of conservation objectives, beyond those to manage the target stock. For example, to reduce the risk of seabird bycatch (e.g. albatrosses), the Australian fishing industry was initially required to use demersal trawls instead of longlines until mitigation measures were identified. There is also a general 50 tonnes bycatch limit (total) for any species in CCAMLR areas where there is no assessment. In addition, there was a "move on" rule applied in the HIMI fishery if the bycatch of any single species exceeded 5% of target species in any single shot (CCAMLR, 2004).

When Australia commenced the fishery in the 1996 1997 season, official landings were only 21% of total landings (1927 tonnes, IUU landings were estimated to be 7117 tonnes, respectively); i.e. in total exceeding the catch limit by 238% (CCAMLR, 2016). Only demersal trawling was allowed, and the fishing ground had no specific protected areas. Early in the HIMI fishery, a typical fishing trip might be spent in different ocean regions (such as Macquarie Island or the Indian Ocean high seas) and also targeting mackerel icefish (*Champsocephalus gunnari*) at HIMI. In recent years, the HIMI vessels predominantly catch toothfish in the HIMI region (over 90% of annual gross value over the past decade; Patterson *et al.*, 2017). Bycatch ranges between 6 and 13% of the total catch (or up to 26% if elasmobranchs cut off longlines before landing are included), primarily comprising rattails *Macrourus* sp., skates *Rajidae*, unicorn icefish *Channichthys rhinoceratus*, and grey rockcod *Lepidonotothen squamifrons*, all of which have bycatch limits that have never been exceeded (CCAMLR, 2016).

Today, the HIMI fishery is undertaken by four entitled vessels, licensed to fish using three different gear types, with 100% observer coverage of every fishing trip (Table 1). A considerable part of the fishing ground is protected from fishing in the form of an IUCN Category 1a marine reserve declared in 2002, and extended in 2014, covering over 71 200 km^2 of the area (over 39% of waters shallower than 1000 m; Figure 1). The quota for the 2015 2016 fishing season was 3405 tonnes, representing over 14% of global landings of Patagonian toothfish and 12% of the global toothfish volume (including Antarctic toothfish).

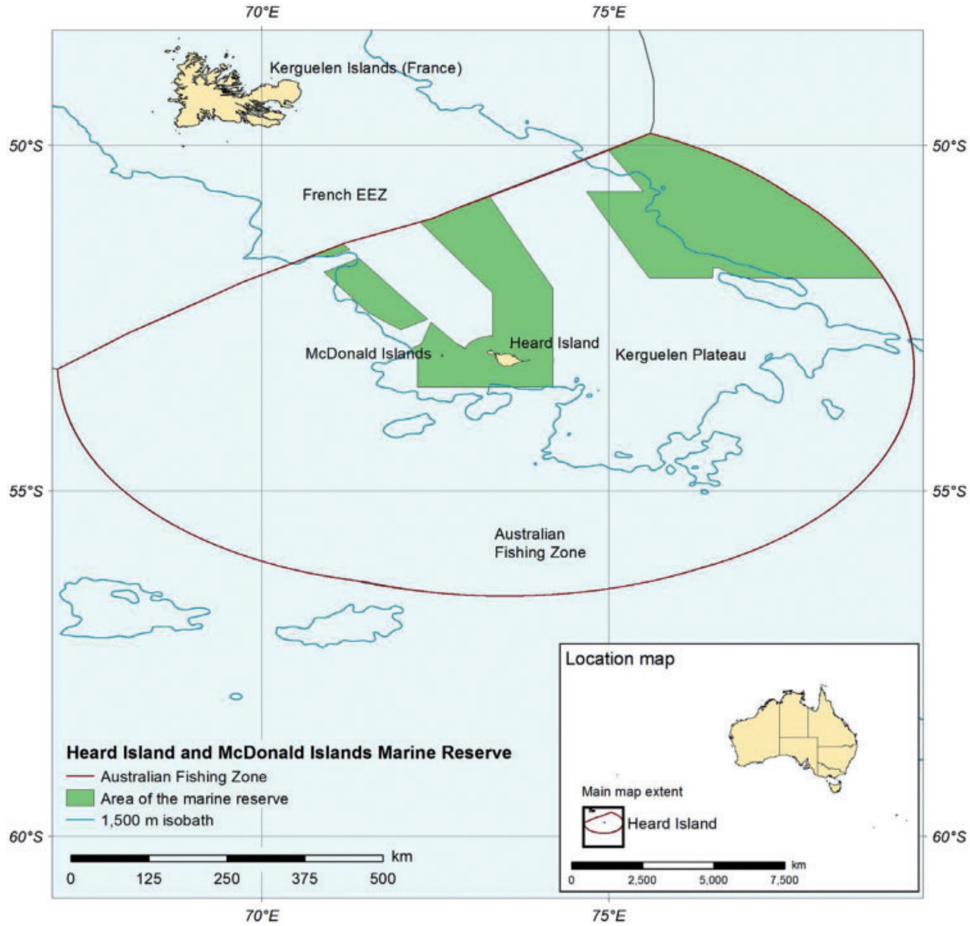

Figure 1. Map of HIMI fishing grounds and marine reserve (*Source:* Patterson *et al.* 2017).

Table 1. Gear characteristics of the Australian fishery for Patagonian toothfish at HIMI during the fishing season 2012 2013 (latest year when all three gears were used).

Gear	Longline	Trawl	Pot
Depth range (m)	500 2370	262 886	500 1500
Effort (fishing days)[a]	263	106	8
Patagonian toothfish landings (t)[a]	1356	1360	8
Mean size of target (kg)[b]	7	4	15
Fishing season	1 May 14 Sep[c]	1 Dec 30 Nov	
Vessels	Antarctic Chieftain,[d] Austral Leader 2, Isla Eden	Southern Champion	Austral Leader 2

[a]CCAMLR 2017.
[b]Austral 2017c.
[c]"Possible extension from 15 to 30 April and 15 September to 31 October each season for any vessel that has demonstrated full compliance with CM 25-02 in the previous season" (CCAMLR 2016).
[d]Not operated by Austral Fisheries.

The focal fishing company in the case study, Austral Fisheries Pty Ltd (hereafter referred to as Austral), has conducted all trawl and pot fishing since the start of the fishery, and commenced long lining in 2008 (another company has operated longlines since 2003). Based on the importance of both stock status and gear for catch efficiency (measured as catch per unit effort, CPUE), and associated fuel use and GHG emissions of seafood products (Ziegler *et al.*, 2016a), the fuel efficiency for each fishing method, and over time, are highly relevant from a GHG emission perspective.

Ecological risk assessment

The ERAEF method used for assessing ecological risk in this fishery is a hierarchical framework, with qualitative, semi quantitative, and fully quantitative tools. A full description of the ERAEF method is provided in Hobday *et al.* (2007). In short, the method systematically identifies ecological risks from fishing in order to inform management actions. Risks are estimated in five ecological components representing the ecosystem: key/secondary commercial species (hereafter referred to as target), byproduct (non target species which may be retained for sale), bycatch (non target species usually discarded) species, pro tected species, habitats, and ecological communities. The assess ment procedure has four stages, providing cost effective screening of risks and prioritization of management actions:

1. Scoping	Description of fishery, units to be assessed, risks from the fishery, and management objectives
2. Level 1: Scale intensity consequence analysis (SICA)	Expert judgement to screen out low risk activities and possibly entire ecosystem components
3. Level 2: Productivity susceptibility analysis (PSA)	Empirically based, semi quantitative, and precau tionary approach to uncertainty (more false positives than false negatives) to screen out low risk species, habitats, or communities
4. Level 3	Model based, quantitative, e.g. regular stock assessment, ecosystem modelling for species, habitats, or communities

In this study, results [i.e. level 1 scale intensity consequence analysis (SICA) and level 2 productivity susceptibility analysis (PSA) since no level 3 assessment was performed] were extracted from existing ERAEF reports (the fishery has been assessed twice, in 2006 and 2016, with reports dated 2007 and 2018; reports used are listed in Supplementary Data S2). Furthermore, general descriptions of the fishery and potential risks based on the scoping phase were used to describe the development of the fishery. ERAEF assessment of ecological communities has only been completed at level 1. Benthic habitat risks were not assessed, but pelagic habitats are included in the 2018 report; other reports, such as Welsford *et al.* (2014), are used here to assess seafloor pressures. ERAEF risk to bait species used in longlining and traps was not conducted.

Life Cycle Assessment

The overall goal of LCAs depends on the intended application but is often intended to identify improvement potentials (or "hot spots") of a production system and avoid problem shifting (be tween different types of pressures or production phases) from a po tential change in production. The environmental pressures from each production phase, such as fishing or transportation, are quan tified for a range of environmental concerns, such as global warm ing potential and eutrophication potential (Finnveden *et al.*, 2009). The approach of LCA consists of four stages, although most often it is iterative due to, for example, data deficiency:

1. Goal and scope	Methodological decisions such as object of study called functional unit (FU), system boundaries, allocation of environmental burdens between products and co products, which environmental impacts to include, etc.
2. Inventory	Collection of data on inputs and outputs in each step of the life cycle and attributing these to the FU
3. Impact assessment	Based on scientifically established relationships, it transforms separate emissions into equivalents and sort them into impact categories, e.g. Global Warming Potential (where all GHGs are summed into CO_2 equivalents based on the radiative force of each GHG relative to CO_2)
4. Interpretation	Analysis of data in terms of, e.g., data robustness, contribution to results, etc.

As the post landing contributions to GHG emissions of seafood products are in general marginal compared to those of the fishing phase (Ziegler *et al.*, 2016a), focusing on the fishing phase is justi fied in assessing the pressure on climate caused by seafood produc tion. Furthermore, fuel use and catch rates most often drive the fishing performance. Here, the goal was to compare the energy requirements to catch toothfish with trawl and longline (pot is only experimental and midwater trawling is limited) at the start of the fishery and in the most recent years. Detailed data on fuel use was collected from company records, with estimates for longlines primarily based on monthly fuel use accounts per fishing vessel (these vessels predominantly target toothfish at HIMI with long line), whereas primarily fuel budget figures were used for trawl records (these vessels were also active in other fisheries within the same trip which complicates use of fuel accounts); for further details, see Supplementary Data S1. We also included fuel from the catching of bait used in longlining (squid). The functional unit (FU), for which fuel use was estimated, was 1 kg of toothfish prod uct (frozen trunk, i.e. headed gutted tailed) in port. As the reason for fishing and the management focus is to catch toothfish, all fuel use was allocated to the toothfish part of the landing (landed by catch volume has been very low or absent). Using landing volume as FU implies different yields of different gears from different size composition of catches, and different utilization of byproducts (such as heads, cheeks and collars). All catch is today processed on board. By products from processing (mostly guts and off cuts) and non targeted catch (except sharks and rays, which are released if in good condition) are minced on board and discarded at sea outside of the HIMI Exclusive Economic Zone (EEZ), either by steaming outside of the EEZ during a fishing trip, or on return to port.

Other ecologically relevant inventory results used in seafood LCA as proxies for fisheries specific impacts were also quantified per FU, such as bycatch quantity and seafloor pressure. To esti mate seafloor area (SA) pressure of the different gears, we used the areal estimates for the 2014 2015 season as reported for the whole fishery in the most recent ERAEF reports: in total 21.5 km^2 for demersal trawling, and for longline estimated from the total:

$$SA = (W * L * H)$$

where H is the number of hooks used (16 million), L is the length between hooks (1.4 m), and W is the width of gear (0.4 m). We note that the demersal longline estimate may be conservative, since considerable movement of the gear on the seafloor has been observed in the fishery ($W =$ 10 m; Welsford *et al.*, 2014). There are many factors affecting the actual seafloor pressure of the two gears (e.g. extent of removal of fauna, vulnerability of different species, aggregation of effort), and W varies also for trawling in the fishery depending on boat and gear configuration ($W =$ 100 160 m for demersal trawling; Welsford *et al.*, 2014). The SA esti mates provided here are thus indicative of differences between the gears, rather than robust absolute figures, since the latter requires further investigation, which is not within the scope of this paper. Total SA per gear type was divided by landings from the same fishing season for m^2/FU. Estimating discard ratios in kg per FU from bycatch amount is not straightforward in the HIMI fishery, since some bycatch are released (skates and rays in good condition); bycatch amount reported in the latest ERAEF reports were used. CCAMLR (2017) data were used for total ef fort and landings per gear at HIMI, Australian Antarctic Division (AAD) data were used for commercial catch and effort of the

Austral fleet, and Austral provided LCA inventory data such as fuel use (Supplementary Data S1).

Finally, GHG emission reduction opportunities were estimated through theoretical change in parameters affecting fuel use per landing: CPUE, technology, skipper, yield, and bait source.

Results

ERAEF results

The first ERAEF (2007) reported very low interactions with birds and mammals for the legal HIMI fishery, and a low SICA risk score for protected species (Supplementary Data S2); a total of three birds had been killed since the start of the longline fishery, and a total of ten birds were observed as killed in the demersal trawl fishery from 1997 to 2005. However, IUU catches were noted as a hazard. The level 1 SICA analysis covered all ecosystem components except for habitats due to data limitations (Figure 2), and the need for risk assessment of habitats in the trawl fishery was noted (20 t of benthic invertebrates and 75 t of rocks had been entangled in the gear during a 5 year period). For both fisheries, level 1 SICA screened out one ecological component (protected species) based on effective management arrangements in place and thus low risk of being caught, even for the most vulnerable species, black browed albatross (*Thalassarche melanophrys*). The level 2 PSA assessed risks to target and bycatch species, but not for communities due to lack of an underpinning trophic model. The analysis indicated high risk for toothfish (target component) in both trawl and longline fisheries, as well as for several species in the byproduct/bycatch component, in particular skates, due to their inherent vulnerability to fishing and catch rate in longline fisheries (Figure 3). For the trawl fishery, 52 out of the 87 species assessed at level 2 were found to be at potentially high risk, and 13 out of 19 species for longline, respectively (Supplementary Data S2). For both fishing methods, most species classified at high risk were due to data deficiency (missing biological information or lack of spatial distribution information).

In the recent ERAEFs, the number of activities causing hazards was lower than in 2007 (Supplementary Data S2). Toothfish is now under a biennial stock assessment (equivalent to ERAEF level 3, thus not included in the latest ERAEF) and stock status has been assessed as not overfished (i.e. the biomass above limit reference points) nor subject to overfishing (i.e. the fishing mortality lower than limit reference points) since 2006 (Patterson *et al.*, 2017). While trawl effort has decreased and quotas have increased, longlining effort increased in both number of days (from roughly 50 in 2003 to a record of 718 in 2015) and number of hooks per fishing day (from roughly 13 000 in 2003 to 22 000 in 2015) (CCAMLR, 2017). Despite this, risk to birds did not increase in the ERAEF (Supplementary Data S2). The increased longline effort has, however, contributed to higher mortalities of elephant seals *Mirounga leonina* (8 mortalities in 2016; Patterson *et al.*, 2017), but according to ERAEF most likely not at a rate that puts the population at risk. Furthermore, longlining has a lower selectivity for skates and rays compared to demersal trawling. For risks to benthic habitats, the ERAEF refers to findings in Welsford *et al.* (2014): Based on where vulnerable organisms occur in relation to fishing effort concentration, and the fact that the marine reserve protects more than half of structure forming biota, risks to benthic habitats were assessed to be low. One ecosystem component, ecological communities, is still considered to be at higher risk due to lack of knowledge about broader ecosystem effects from removal of different sizes of toothfish (Table 1; Supplementary Data S2), but the report notes that the precautionary management approach takes into account predator prey relationships, and monitoring of top predators (diet, reproductive rates, and abundance) is done.

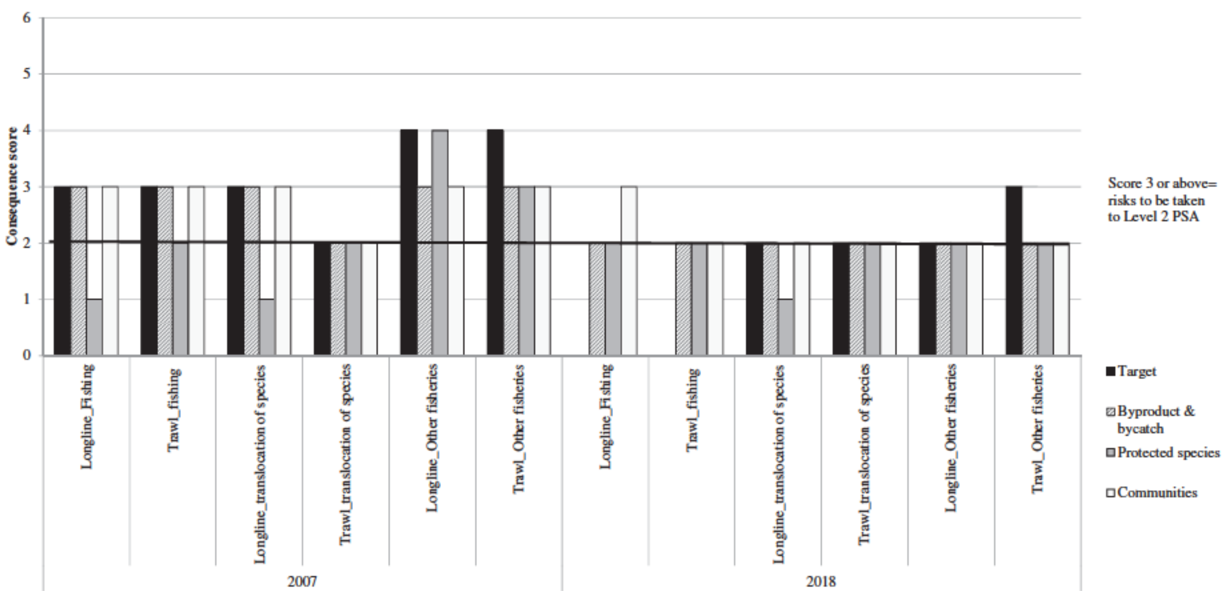

Figure 2. Level 1 SICA scores for hazards identified to be at higher risks (exceeding the bar, i.e. a consequence score of ≥ 3) in the 2007 assessments and the same risks in the 2017 assessments. No new risks were identified between the assessments. The consequence score definition is: 1 = negligible, remote likelihood of detection at any spatial or temporal scale; 2 = minor, occurs rarely or in few restricted locations and detectability even at these scales is rare; 3 = moderate, moderate at broader spatial scale, or severe but local; 4 = major, severe and occurs reasonably often at broad spatial scale; 5 = severe, occasional but very severe and localized or less severe but widespread and frequent; and 6 = catastrophic, local to regional severity or continual and widespread.

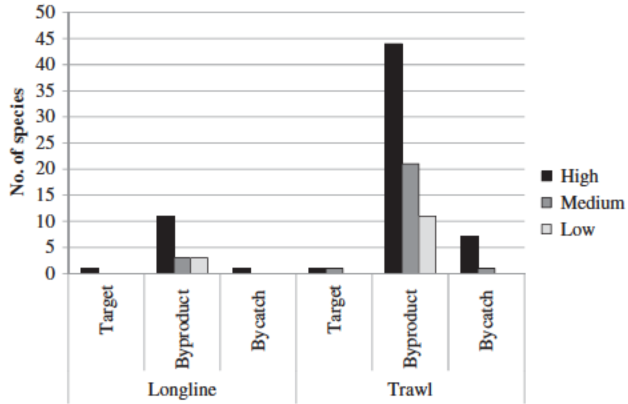

Figure 3. Level 2 PSA results for the toothfish fishery ERAEF in 2007. Protected species were screened out during Level 1 SICA, and thus not assessed at Level 2 PSA.

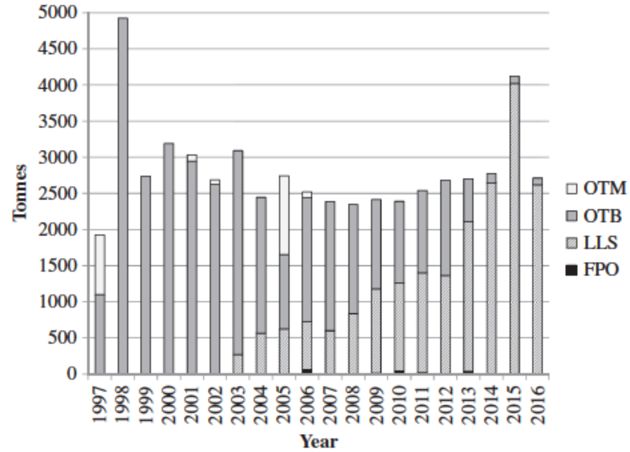

Figure 4. Historical development of landings per gear (OTM = midwater trawl; OTB = demersal trawl; LLS = longlining; FPO = pots) based on CCAMLR (2017).

LCA inventory results

Fuel use from fishing was confirmed as the dominant contributor to GHG for the toothfish fishery Austral's organisational LCA found that nearly 90% of the GHG emissions of the product (from fishing to retail) were attributable to fishing at sea for the years 2014 and 2016 (Supplementary Data S1).

Landings by different gears have changed considerably over time (Figure 4). Catch rates were initially, in general, higher but more variable, and have stabilized at a lower level in the last decade compared to early fishing (Figure 5). Trawling during 1998 2000 had, on a trip basis, average catch rates of 17 28 tonnes/day, whereas during 2014 2016, the equivalent was between 8 and 17 tonnes/day (Supplementary Data S1). This is expected during the fishing down phase of a developing fishery. With the catch efficiency, gear use and targeting pattern at the start of the Australian fishery, fuel consumption for the Patagonian toothfish fishery at HIMI was 0.7 L/FU in 1998.

In 2016, fuel consumption per FU had increased considerably. The annual average fuel consumption was 4.0 L/FU when trawling and 2.4 ± 1.7 L/FU for longline. The difference is smaller if the comparison is based on live weight: 2.6 L/kg for trawling and 1.7 ± 1.2 L/kg for longlining, respectively (Figure 5). This is due to higher product yield in longlining from use of byproducts. The variability in fuel use for longlining is derived from different fuel efficiencies of the three different boats operating, as opposed to trawling, which is only done by one vessel. The inherent fuel consumption per fishing day is lower for longlining than trawling, but the fuel efficiency per kg is to some extent counteracted by lower catch rates for longlining compared to trawling. Furthermore, adding fuel required from bait fishing makes longline fishing less efficient. During 2014 2016, bait use (squid) increased from approximately 0.14 to 0.23 kg/kg live weight toothfish at catch (due to more hooks per volume of landing). Austral estimated fuel use requirements from bait use to be marginal compared to fuel use in fishing, 0.08 L/kg live weight in 2016. This estimate was likely based on fuel consumption of a certain vessel size, catch rate, and fishing pattern of an industrial fleet targeting squid (resulting in 0.36 L/kg bait) due to lack of LCA data. However, there are large additional energy requirements using lights when catching squid (Matsushita *et al.*, 2012) that were not considered, and fuel efficiency to catch squid may vary vastly depending on gear type 0.27 1.88 L/kg (Park *et al.*, 2015). Assuming the worst case scenario (1.88 L/kg), the contribution to fuel use from bait collection could therefore be up to 0.42 L/kg live weight toothfish.

The areal seafloor pressure for longline caught toothfish was 3 and 159 m^2/FU for demersal trawling in the 2014 2015 season. Bycatch ratios in the same season were 0.12 kg/FU for trawling and 0.14 kg/FU for longlining.

Scenarios for GHG emission reduction showed that an increase in CPUE would have the largest improvement potential, whereas industry measures, such as technological investment, had lower emission reduction potential (Table 2).

Discussion

Different aspects to seafood sustainability

From an ERA perspective, management has been effective in reducing local ecological risks from the Patagonian toothfish fishery at HIMI over time. Present fishing mortality and stock biomass are assessed as ecologically sustainable, and no IUU vessels have been detected inside the HIMI EEZ since 2005 (CCAMLR, 2016). Management actions have included broad data collection and scientific analysis in combination with a set of management and conservation tools including (amongst others): quotas, technical measures to reduce bycatch, fishing gear restrictions, protected areas, and seasonal restrictions. In imposing these management arrangements, some may be seen in retrospect as maladaptive, such as only allowing demersal trawling, which was associated with larger seafloor disturbance. Other measures result in tradeoffs that may be required to fulfil conservation objectives, such as extra fuel needed for steaming to dump offal outside the EEZ to avoid attracting birds. To this end, the ecological risks were initially higher (mainly based on substantial data deficiency, which, by default, equals to a precautionary high risk in the ERAEF approach, Hobday *et al.*, 2011), but the fuel consumption per fish caught was lower on an annual basis. While ecological risks have decreased over time, fuel use per landing has instead increased. However, the fuel efficiency in the early stages of a new fishery is not a realistic target, since some of the early catches come from reduction in biomass until equilibrium is reached.

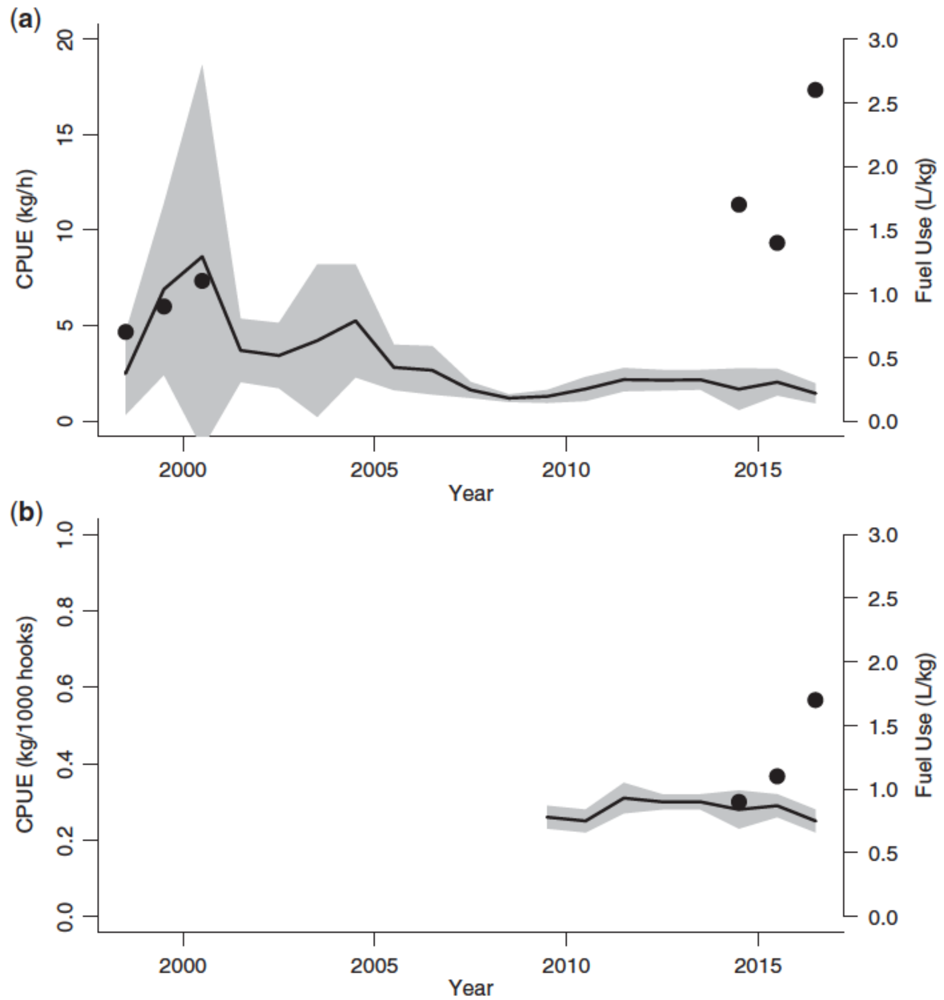

Figure 5. Annual average commercial CPUE (line, shaded area represents standard deviation) for (a) demersal trawling and (b) longlining with annual fuel use (points) by Austral for Patagonian toothfish at HIMI based on AAD data.

Table 2. Opportunities for emissions reduction (only combustion) of longlining for Patagonian toothfish at HIMI (Supplementary Data S2).

	Change variable	Description	Fuel use (L/FU)	GHG (CO_2e kg/FU)[a]	% reduction
Present situation (year 2016)		CPUE 0.19 tonne GWT/1000 hooks set, bait use 0.22 kg/kg	2.6	7.0	
Management	Achieve higher CPUE (2014 level)	CPUE 0.29 tonne GWT/1000 hooks set	1.3	3.58	49
Industry	New generator[b]	Fuel use 20% for the Atlas Cove	2.5	6.8	3
	Skipper effect	The most catch efficient vessel (in L/kg)	1.9	5.2	25
	Improve utilization	Improve yield by 10%	2.3	6.4	9
	Use most fuel efficient squid bait	0.27 L/kg bait (Park *et al.*, 2015)	2.5	6.9	2

[a]Using 1 L fuel 2.72 kg CO_2e (Supplementary Data S2).
[b]Planned in 2018 by Austral Fisheries Pty Ltd.

The general view is that the management of fisheries sets the limits for improvement potential for seafood products (by decid ing on quota, effort, or gear type), and individual fisher decisions are in general less effective than management to reduce fuel use (Parker *et al.*, 2015; Parker *et al.*, 2017, but see also Ruttan and Tyedmers, 2007 and Ziegler *et al.*, 2018). The improvement po tential not only depends on management objectives (Farmery *et al.*, 2014; Svedang and Hornborg, 2015) but also on inherent differences in targeting schooling vs. non schooling species (Farmery *et al.*, 2015). The lower LCA pressures from higher catch efficiency have to be balanced by management with the po tential risk of stock collapse if sustainable fishing mortality cannot be safeguarded, in particular for slow growing schooling fish (Norse *et al.*, 2012). CCAMLR has a more conservative target

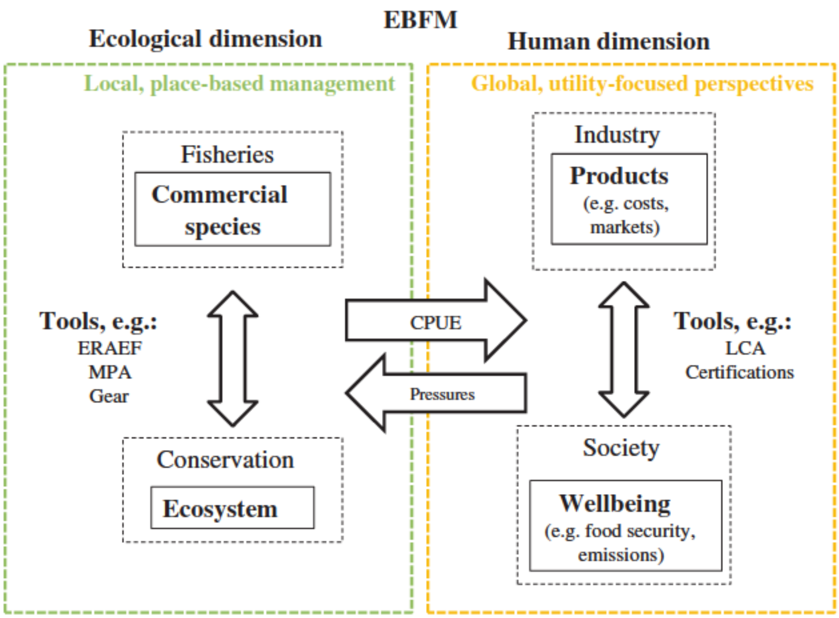

Figure 6. LCA and ERAEF in an EBFM context with emphasis on different stakeholder perspectives and how they are related. Abbreviations: CPUE = Catch-per-unit effort; MPA = Marine-protected areas.

stock management, compared to most other managing organizations, and applied an ecosystem approach early in fishing history (Constable, 2011). The spawning biomass of toothfish fished at HIMI is estimated to be 60 70% of unfished levels (Patterson *et al.*, 2017), i.e. above the biomass level generating maximum sustainable yield. While recognizing that CPUE is not fully indicative of stock status (Maunder and Punt, 2004), fuel use per unit of seafood product would see the largest reductions if CPUE could be further increased in the HIMI fishery through adaptive management.

For fishing companies to reduce their carbon footprint in general, the largest reductions can arguably be made at a fishery management level. For Austral toothfish fishery, changes in CPUE were also found to have the largest influence on GHG emissions. However, in efforts to apply an LCA, there are many data gaps and methodological uncertainties. This affects absolute results of the assessment (amount of GHG emissions), and when following a carbon offsetting scheme (where worst case scenarios should be used), also affects costs for the industry. In global supply chains, lack of LCA data from different suppliers arguably also impedes providing economic incentives from the buyer for low emission practises (e.g. the costly process of switching to more energy efficient LED lamps in squid fishing; Matsushita *et al.*, 2012); regular collection of this type of data into global databases could facilitate LCA based improvement efforts in general, but also carbon accounting initiatives. An example of differences in LCA calculations can be shown from the industrial refrigeration units on Austral's fishing vessels, which currently run on the refrigerant R 22. Here, the effect from fugitive emissions is set to zero when following the Australian National Greenhouse Accounting methodology NGER/NGA 2016 2017, while the Intergovernmental Panel on Climate Change (IPCC) sets the climate pressure of these emissions at 1810 kg CO_2e/kg (Supplementary Data S1). Following the NGER/NGA 2016 2017 guidelines for estimating general leakage rates for industrial refrigeration, a toothfish targeting vessel would leak between 352 and 640 kg/year but that would not contribute to the calculated GHG emissions. If instead IPCC (2014) calculation methodology was followed, this equates to 640 1200 tonnes CO_2e/year per fishing vessel (or an additional 1.35 2.79 kg CO_2e/FU). The use of R 22 is being phased out in Australia, in line with the Montreal Protocol, and this process is costly to industry and will unfortunately not be accounted for as a reduction of GHG emissions from fishing companies.

Lastly, consumer and market demand is an important driver for establishing new fisheries, such as toothfish around the Antarctic, since it contributes to the important whitefish market that has arisen as a result of continued high demand for traditional stocks that have reached the limit of production capacity or been depleted. "Perceptions" on what is sustainable may vary for different food commodities, and for seafood, one may ask if eating fish from a more pristine and distant environment is more of a conflict than eating more heavily exploited species caught locally. Furthermore, selection of trawl fishing grounds at HIMI is currently based on optimizing the size composition of landings for market preferences (i.e. market demand for larger sizes), rather than maximizing volume (Rhys Arangio, Austral, Pers. Comm.). This affects trends in fuel efficiency per landing over time and may be seen as a sustainability trade off induced by consumers.

To this end, is Patagonian toothfish production at HIMI sustainable? Ecological risks are being addressed and mitigated to an arguably larger extent than in many other fisheries. Fuel use per landing has gone from average to the highest amount of fuel use per kg for bottom trawled finfish globally (Parker and Tyedmers, 2015), affected by both biomass and targeting pattern (the selective targeting of larger fish). For longlining, fuel use in the HIMI fishery is at the higher end of hook and line caught finfish globally (Parker and Tyedmers, 2015). Austral addresses this issue through off setting their GHG emissions, which is a further step towards meeting the progressive series of sustainability challenges faced by responsible actors (the moving target of sustainability is discussed in Tlusty *et al.*, 2012). Still, since biomass is inevitably reduced in an exploited stock which strongly affects emission levels, the questions for the future are rather: What is an appropriate biomass in an ecosystem based fisheries management (EBFM) context that allows for high CPUE and low ecological risks? Should energy use and GHG emissions be treated separately through offsetting by industry or included in certification of fisheries? Currently, the most energy intensive food production system in the world, demersal trawling for Norway lobster *Nephrops norvegicus* (Pelletier *et al.*, 2011), is certified as sustainable by MSC (MSC, 2018). FAO (2016) consider inclusion of GHG and energy use into ecolabels as a progress towards addressing the three pillars of sustainability. However, to be included in certification criteria, decisions would be required to determine cut off levels to be categorized as environmentally sustainable, for each aspect separately but also in relation to each other. This raises questions on priorities (e.g. low bycatch rates over high fuel consumption?) and relevant comparisons (e.g. should cut off criteria for emission levels be compared to other seafood products or all food commodities?). For offsetting to become an industry norm, improved market responsiveness is also needed, such as a price premium (Martin Exel, Austral, Pers. Comm.).

Dual methods to assess sustainability

The HIMI fishery has state of the art data collection and assessments. The ERAEF updates are jointly funded by industry and management, and informed decisions on fishing opportunities and broader management actions to conserve the ecosystem. Accounting for, and offsetting, GHG emissions is a costly industry initiative, both in terms of time to perform the assessments and in paying for offsetting and reduction strategies. With global concerns rising over the need to implement immediate actions at every level of decision making to reach set targets (Figueres *et al.*, 2017), and LCA methods being used to inform decision making in other areas such as the European Union directive on biofuels (EC, 2017), the question is if and how GHG assessments should be included in fisheries management in the future?

Given the strong influence of management on GHG emissions in fisheries, a first step could be to monitor fuel use as a performance indicator. This would facilitate delivering LCA perspectives, which are currently time consuming. As a next step, it is important to find common ground on what characterizes sustainable use based on EBFM objectives (Pikitch *et al.*, 2004). While ERAEF provides important decision support for place based EBFM, identifying when a management system is maladapted in terms of fishing economy (fuel use) and off site impacts (GHG) through low CPUE is a starting point to discuss improvement potentials (Figure 6). Furthermore, as LCA has a strong connection to supply chain stakeholders (based on industry and societal interest in results), routine LCA inclusion in assessing sustainability of seafood may provide further progress towards including the human dimension of EBFM. By studying the performance of a fisheries production system (i.e. "pressures per quantity of product"), insights may be provided on how a stock is best utilized from a societal perspective (e.g. Driscoll and Tyedmers, 2010; Farmery *et al.*, 2014; Ziegler *et al.*, 2016b) and illustrate quantified trade offs of management actions (either based on values, such as protecting sensitive species, or unintentionally; Hornborg *et al.*, 2012, Hornborg *et al.*, 2017) forming the basis for discussions with stakeholders on what are acceptable pressures and trade offs.

Supplementary data

Supplementary material is available at the *ICESJMS* online version of the manuscript.

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