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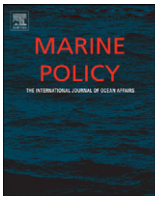

Integrated environmental assessment of fisheries management: Swedish *Nephrops* trawl fisheries evaluated using a life cycle approach

Sara Hornborg [a,b,]*, Per Nilsson [b], Daniel Valentinsson [c], Friederike Ziegler [a]

[a] *Swedish Institute for Food and Biotechnology, Sustainable Food Production, Sweden*
[b] *University of Gothenburg, Department of Marine Ecology, Sweden*
[c] *Swedish University of Agricultural Sciences, Department of Aquatic Resources, Institute of Marine Research, Sweden*

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ABSTRACT

Fisheries management needs to broaden its perspective to achieve sustainable resource use. Life cycle assessment (LCA) is an ISO standardized method to evaluate the environmental impacts of products using a broad and systematic approach. In this study, the outcome of a management regime promoting species-selective trawling in Swedish *Nephrops* trawl fisheries was studied using LCA methodology by quantifying the impacts per kilogram of landing using two different fishing methods. Demersal trawling has previously been found to be both energy intensive and destructive in terms of seafloor impact and discards. It is demonstrated that species-selective trawling fulfils management objectives, although with tradeoffs in terms of fuel consumption and associated GHG emissions. To prioritize between impacts, one must be aware of and quantify these potential tradeoffs. LCA could be an important tool for defining sustainable seafood production as it can visualize a broad range of impacts and facilitate integrated, transparent decision making in the seafood industry. It is also concluded that, with current LCA methodology, use of total discarded mass could increasingly be distinguished from potential impact by applying two new concepts: primary production requirements and threatened species affected.

1. Introduction

Managing fisheries is complex. Measures are often determined based on uncertain data, in a limited time, and with a range of different motives – economic, social, and biological – predominantly lacking the integrated perspective [1]. Several of current fishing regimes have been found to have severe negative impacts, not only on targeted species, but also on whole marine ecosystems, and are accordingly being questioned [2,3].

Discussions of sustainable fisheries management have focused mainly on stock recovery and sustainable exploitation rates [4], whereas possible consequences of measures taken to improve or sustain stock status, such as increased energy consumption or seafloor disturbance, are seldom integrated in the same management context. This may result in incoherent management decisions, which in turn lead to overcapacity and fuel subsidies. Besides improving fisheries economics [5], there is a cumulative need to mitigate the net effects of a range of anthropogenic stressors on the marine environment [6].

The need for an overall evaluation of the impacts of management measures can be seen in recent developments such as increasing consumer awareness and the ongoing reform of the EU Common Fisheries Policy [7,8]. Broader approaches, such as strategic environmental assessments (SEA), are asked for to pre-evaluate expected impacts of proposed fisheries management measures in the EU [9]. As a complement, there is a need for the post-evaluation of broader environmental impacts of measures taken, in order to increase the transparency of the seafood sector.

1.1. Life cycle assessment and seafood production

Life cycle assessment (LCA) is an ISO standardized methodology that relates resource use and environmental impacts to a product from a cradle-to-grave perspective [10]. In seafood production, early LCAs generally concluded that, of traditional impact categories, such as greenhouse gas (GHG) emissions, the fishing phase dominated the life cycle due to the fuel intensity [11,12]. Fisheries management, by influencing, for example, the type of gear used, may have implications for the resource use of fisheries. Overcapacity and decreasing fish stocks are expected to lead to excess effort, which could in turn influence fuel consumption [11,13–15]. By shifting from a product to a management perspective, LCA could provide a comprehensive and transparent

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* Corresponding author. Tel.: +46 10 5166696; fax: +46 31 833782.
E-mail address: Sara.Hornborg@sik.se (S. Hornborg).

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evaluation of the overall environmental implications of fisheries management measures by comparing the environmental impacts per seafood product, revealing the magnitudes of impacts and the potential tradeoffs between them. So far, the only study using LCA to evaluate various fisheries management scenarios identified a range of 17–116 l of diesel per ton of landed herring [16]. However, biological impacts were not to a great extent taken into consideration in LCA's as is attempted here.

If one considers biodiversity loss [17], fish stock depletion [7], trophic interactions [18], size alteration [19], and seafloor disturbance [20], which are not usually considered at present [21], the impacts of fishing become even more serious. The problem has been lack of methodology. One study that tried to gage discards and seafloor area disturbed per kg of landed Norway lobster (*Nephrops norvegicus*) indicated vastly different biological impacts for different fishing practices: 15,000 m^2 of seafloor was found to be affected by trawling while creeling affected only 1.8 m^2 of seafloor, with total discards of 4.5 kg versus 0.36 kg [22].

The present study considers differences in appropriation of primary production from discards as a differentiated discard impact for an LCA framework. Primary production requirements (PPR) are considered, because primary production limits global fisheries yield [23] and gives a rough proxy for trophic interactions such as depletion of top predators, an established fisheries impact [17,18].

A new LCA category included is the potential discard impacts on vulnerable, endangered, and critically endangered (VEC) fish species [24]. Fisheries are often the reason why fish are under threat, so it is important that this impact should inform practice. The International Union for Conservation of Nature (IUCN) Red List is intended to protect species not specifically covered by a management framework, as is often the case with discarded species, and has been shown to be adequately correlated with the results from stock assessments [25,26]. Landed fish species are not included, but are considered as a managed, hence controlled, impact.

1.2. Case study: The Swedish Nephrops fishery

Nephrops is one of the most valuable species in Swedish fisheries. The fishery is located in the western coastal waters, the Skagerrak and Kattegat (ICES area IIIa SD 20 and 21, Fig. 1) and is conducted using demersal trawls and creels. The recommended and agreed-on total allowable catch (TAC) for the area was 5170 t in 2010, of which the Swedish portion was 1359 t [27].

The *Nephrops* trawl fishery in the North-east Atlantic is known to have one of the highest discard ratios in the world [28]. Discard is the portion of the catch that is thrown back to sea, in amounts that vary strongly with, for example, area fished, season, management policies, economic incentives, and fisherman behavior. In *Nephrops* trawl fisheries, by-catch consists to a great extent of fish species many of which are restricted with quota. To decouple *Nephrops* catches from quota-filled fish species and keep the fishery open when quotas on other species are closed, in 2004, the Swedish Board of Fisheries developed and implemented a species-selective grid of Nordmøre type (Fig. 2) which releases fish through an escape window [29].

Fishing days permitted with conventional trawls have gradually been reduced since 2004 in accordance with long-term management for cod recovery by reducing fishing mortality of cod [30,31]. Vessels trawling without sorting grids are restricted by both TAC and effort measures in line with the updated Cod Recovery Plan. Grid trawling is excluded from effort regulation due to low by-catches of cod, only being subject to a national level effort limitation [32]. Furthermore, vessels with sorting grids are allowed access to some areas closed to conventional trawling, such as a no-trawl coastal zone and parts of a marine protected area in the Kattegat (Fig. 1). From having been mainly a mixed fishery, catching *Nephrops* and fish, grid introduction has led to the development of a separate single-species fishery for *Nephrops* [33]. In 2009, grid trawling accounted for 50% of total Swedish *Nephrops* landings; conventional trawling landed 30%, while creeling landed the remaining part (Fig. 3).

Selective fishing practices, however, may not reduce overall pressure on the marine environment, as landings per effort are lowered for gear that in this case are already characterized by high fuel consumption [11,14,22] and seafloor disturbance [20]. Species-selective fishing is more vulnerable when catches of *Nephrops* are low, and could accordingly increase resource wastage. At the same time, use of sorting grids could represent an improvement, as sorting time decreases, contributing to higher quality and mitigating overcapacity. Expert opinions on marine ecosystem stressors urge immediate action to reduce GHG emissions and restore the structure and function of marine ecosystems [34]. It is therefore important that broader evaluations establish a proper framework for determining whether cutting the fleet or making it less effective would contribute most to reaching management goals.

1.3. Aim of the study

The present study aims to evaluate the broad environmental implications of having the *Nephrops* trawl fishery in Sweden structured into two separate fisheries in response to EU regulations to protect cod. This will be done using LCA expanded with potential biological impacts. More specifically, potential tradeoffs between the environmental impacts of introducing the species-selective grid, such as increased seafloor area swept or fuel consumption, are quantified in relation to possible biological implications, such as discard impact on threatened species (VEC) and trophic interactions (PPR).

An additional aim is to advance the development of LCA methodology with regard to the inclusion of indicators of differentiated discard impact (VEC and PPR) in the framework.

2. Methods

2.1. General life cycle assessment (LCA) methodology

LCA consists of four phases: goal and scope, inventory, impact assessment, and interpretation of results. During the goal and scope phase, system boundaries for the study are defined and the product of focus, i.e., the functional unit (FU), is specified. In the next step, inventory, all resource use and emissions of interest according to the goal and scope are quantified in relation to the functional unit. In the impact assessment, collected data are grouped in categories of potential environmental impact. The most commonly used impact category is global warming potential (GWP), in which all GHG emissions caused in the product's life cycle are grouped and weighed together according to the latest scientific findings of the Intergovernmental Panel on Climate Change (IPCC). During the interpretation of results, the robustness of the results is tested, for example, by sensitivity- or uncertainty analysis. The main areas of application of LCA results are in product development, environmental management, and communication (e.g., eco-labels).

2.2. Methodological choices for this study

LCA was chosen because it is the most holistic product-oriented method for assessing environmental impacts and can identify improvement potentials [16,35–37], and because of a general interest in using LCA as a management tool. This

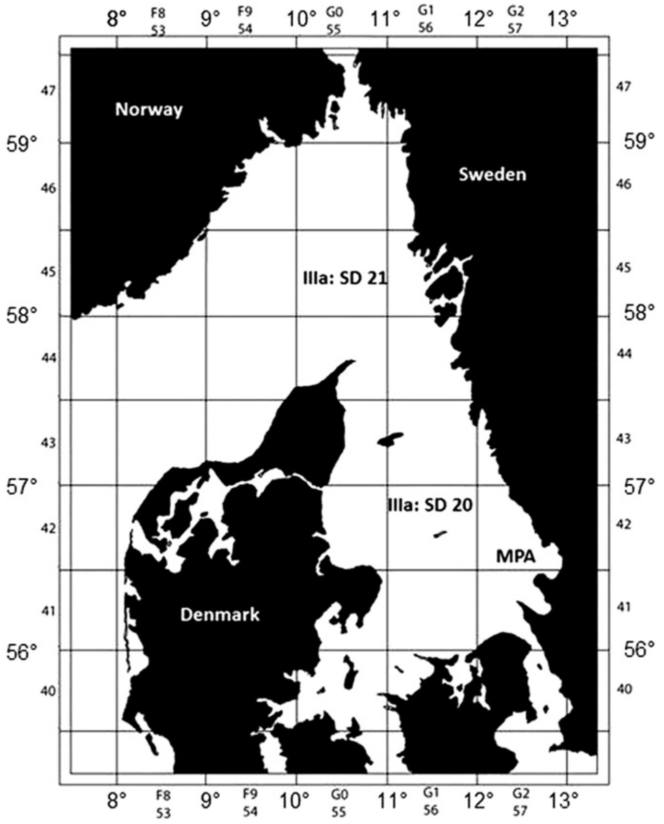

Fig. 1. ICES area IIIa SD 20 and 21.

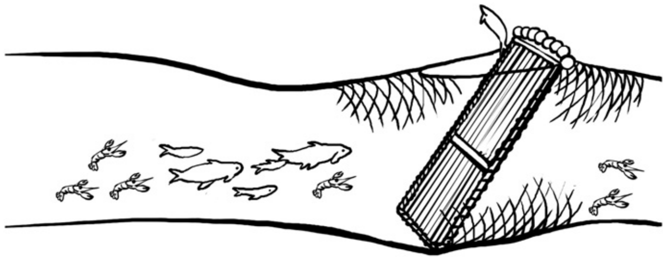

Fig. 2. The *Nephrops* sorting grid (illustration: Jürgen Asp).

particular fishery was chosen to build on the findings of an earlier study [22] of the wider environmental implications of promoting sorting grid use in trawl fisheries.

System boundaries include Swedish trawl fishing operations targeting *Nephrops* in terms of fuel production and consumption, seafloor disturbance, and impacts of discards and landings (Table 1). The time frame is one year, 2009, providing a snapshot of the fishery. Production of fishing vessels and gear was not included because they are known to make a minor contribution to the total result [38], especially in resource-intensive fisheries such as trawling, and are also an equal background system, since the same boats use both types of gear. The functional unit (FU), 1 kg of landed total catch, was chosen because this is the managed output of the different fishing fleets and because grid landings are replaceable with landings from conventional trawlers targeting *Nephrops*, regardless of species composition.

2.3. Data sources, assumptions, and limitations

All studied impacts were analyzed separately for Kattegat and Skagerrak, as some differences between the areas, such as marine habitat, species distribution, and, to some extent, different management measures, could affect results. A marine protected area in the Kattegat affects the fishing grounds available for the gear and the no-trawl coastal zone extends three nautical miles in the Kattegat, versus four nautical miles in the Skagerrak. The sampled trips belong to *Nephrops*-targeted operations as defined by the Board of Fisheries, i.e., a minimum of 10% of the landings by mass consist of *Nephrops*. Discard survival rate was set to zero, although gear type and species exhibit differences, as too many factors interfere in order to include survival rates [39].

A fuel consumption model based on installed engine power (kW) [40] was applied to Swedish logbook data and adjusted to usage of only 40% of kW during trawling, based on estimates from interviews with fishermen (12 boats landing approximately 25% of the *Nephrops* trawl landings). A vessel's diesel consumption per trawling hour is assumed to be approximately the same whether or not the grid is used, although absolute figures could be influenced by differences in trawling depth, gear configuration, speed, location, and weather [41]. Energy use per landing is hence mainly affected by catchability. A maximum transportation speed was applied to every first haul in a day, assuming 2 h for grid trawling in the Skagerrak (3 h for conventional) and 1.5 h for grid trawling in the Kattegat (2.5 h for conventional). Model assumptions are tested in a sensitivity analysis. Data collected and compiled by the Board of Fisheries on absolute annual fuel use by fishermen were not made available in a format detailed enough for the purpose of the present study for confidentiality reasons, but were used for double-checking. Combustion figures for diesel (MK1) were taken from the Swedish Petroleum & Biofuel Institute (www.spbi.se).

In terms of seafloor disturbance, area swept was assessed by differentiating between the proportional use of single versus double trawls. Gear indices were based on data from Nilsson

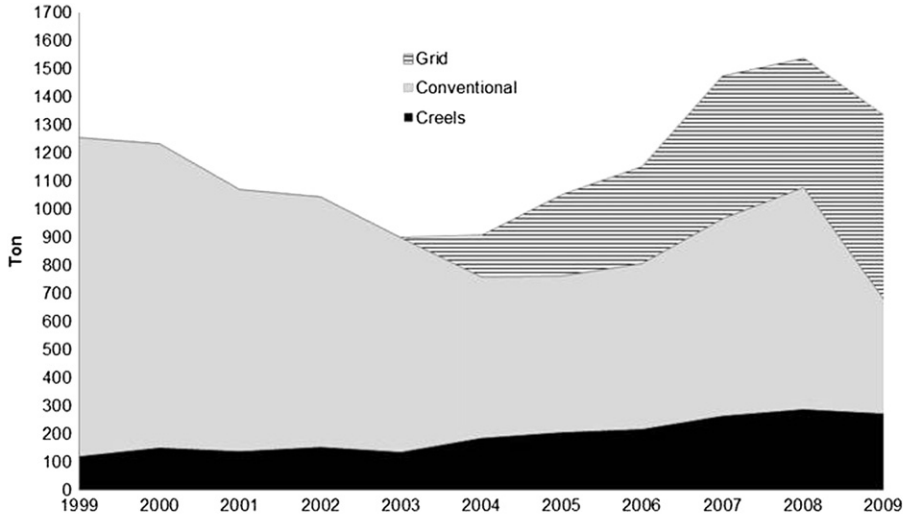

Fig. 3. Contributions of different types of gear to Swedish *Nephrops* landings, 1999–2010.

Table 1
Resource use (fuel) and impacts assessed per functional unit in this study.

Impact	Unit
GWP	CO_2e
Fuel use	Liters diesel
Total discard	Kg
PPR	kg C
VEC	Individuals of threatened species (vulnerable, endangered or critically endangered according to IUCN criteria)
Target stock	Qualitative + kg juveniles discarded
Seafloor	m^2

and Ziegler [42], i.e., 0.22 $km^2\,h^{-1}$ for single trawls versus 0.39 $km^2\,h^{-1}$ for double trawls at an average trawling speed of 2.5 knots, and applied to logbook data.

2.4. Data analysis and impact assessment

Based on earlier LCA results for capture fisheries in combination with our own beliefs as to what approximately characterizes a sustainable fishery, we limited the environmental impacts studied to fuel use with associated GHG emissions, discards (i.e., total discard quantity), PPR, VEC, seafloor area swept, and a qualitative discussion of target species impact (Table 1).

Inventory data included were discard quantity, target juveniles caught (see Ziegler et al. [43]), and seafloor area swept (see [22,42,44]). As for impact assessment, GWP [45] and Biotic Resource Use (BRU) [46] have previously been included in the LCA context. BRU captures the amount of carbon from primary production needed in aquaculture to produce 1 kg of wet weight of the cultured species. In this study and for capture fisheries in general, this is better addressed for what it is, i.e., PPR, as was the original intention of the equation [47], because PPR is only one component of the slightly vaguer BRU concept.

Species discarded that have a regional status in Sweden as critically endangered (CR), vulnerable (VU), and endangered (EN) in compliance with IUCN criteria [24], together with (in this case) species under regional protection (Swedish Board of Fisheries, www.fiskeriverket.se), are included as individuals of VEC species discarded per functional unit.

3. Results

Some of the inventory data are only presented as inventory results, while others are characterized.

3.1. Target stock

The definition of the fleet resulted in coverage of 96% of trawl landings. Sorting grid-equipped trawls effectively sorted out undesired fish species according to both logbook and observer data (Fig. 4(a) and (b)). Fig. 4(b) describes the species composition of the functional unit.

The main fish species protected by grid use are cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), hake (*Merluccius merluccius*), and saithe (*Pollachius virens*). For conventional trawlers, cod accounted for 20% of the landings (25% of catch) by mass in the Skagerrak and 8% (9% of catch) in the Kattegat (Fig. 4(a) and (b)). Grid trawling caught mainly flatfishes and juvenile *Nephrops*, notably Common dab (*Limanda limanda*) in the Kattegat.

As for impact on *Nephrops* stock, Sweden landed a total of 1331 t of *Nephrops* in 2009 (quota 1359 t). In mass, *Nephrops* accounts for 96–97% of the landings in grid trawling; in conventional trawling, *Nephrops* accounts for 63% of the landings in the Kattegat and 40% in the Skagerrak. The economic value of the *Nephrops* part of the landings was 98% for grid landings in the Kattegat (87% for conventional); in the Skagerrak, the economic value of the *Nephrops* part was 99% for grid landings but only 75% for conventional trawl landings. The *Nephrops* stock in the Skagerrak and Kattegat is currently considered as being exploited sustainably at a level below a proxy for MSY [48].

Conventional trawling in the Skagerrak was also found to produce a low amount of discarded juvenile *Nephrops* compared with the other categories studied (Table 2). A high amount of discarded *Nephrops* does not necessarily have to represent a significant target stock impact. Discards have been included in assessments since 1999 and the high discard rate is coupled with a large minimum landing size (40 mm carapace length), which allows reproduction before being landed [49]. The total effect on the *Nephrops* population is unknown, but it has been suggested that release of juvenile *Nephrops* reduces instant fishing mortality [50]. According to fishermen, the grid sorts out the largest individuals limited by the distance between the bars, possibly reducing stock impacts as larger females are more fecund.

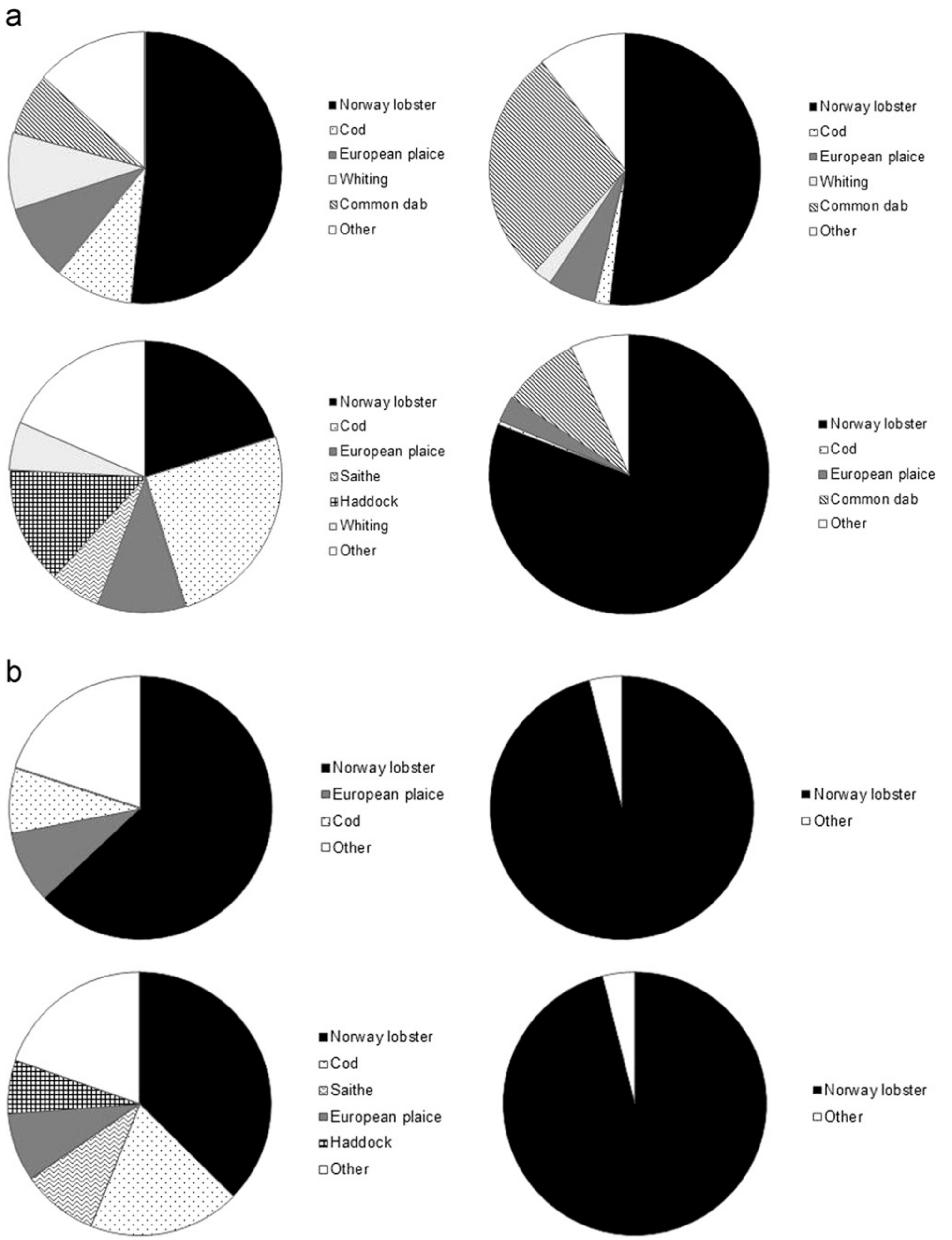

Fig. 4. (a). Catch composition by mass from observer data. Top row, Kattegat conventional (left) and grid trawl (right); bottom row, Skagerrak conventional trawl (left) and grid trawl (right). (b). Landing composition by mass as reported in logbooks. Top row, Kattegat conventional (left) and grid trawl (right); bottom row, Skagerrak conventional (left) and grid trawl (right).

3.2. *Discard quantity and composition*

Discard quantity and species composition differed considerably between the two kinds of trawling (Table 2). Grid trawling in the Kattegat produced the highest amount of discard/FU. However, the main portion of discard species in conventional trawling consisted of valuable and quota-restricted fish species such as cod, haddock, and whiting (*Merlangius merlangus*); in grid trawling, mainly juvenile *Nephrops* were discarded, in the Kattegat together with flatfish of low economic value, such as small dab.

The high dab occurrence in Kattegat grid trawling could be because conventional and grid trawling are more spatially separated in the area (Fig. 5). Survey data have indicated that the occurrence of juvenile dab is much higher closer to the coast.

3.3. *Seafloor and energy use*

Trawling intensity is heavily aggregated (Fig. 5), making certain areas more affected than others. The highest intensity of seafloor disturbance is found within four nautical miles of the coast in the Skagerrak, an area open only for grid trawls and passive fishing gear.

For the Skagerrak, single trawls dominate grid trawling practice, representing 74% of effort, whereas single trawls account for only 47% of conventional trawling effort. In the Kattegat area, generally higher use of double trawls (almost 70% of the trawl effort of both practices) resulted in a slightly higher seafloor disturbance per kilogram of *Nephrops* for both types of gear than did grid trawling in the Skagerrak. Based on these differences, the seafloor area swept per kg of *Nephrops* was in the range of

Table 2
Discard data per kg landed (with s.e.); hauls were aggregated into boat means.

Gear and area	No. of vessels	No. of sampled trips	No. of hauls	Total discard (kg)	*Nephrops* discard (kg)	VEC (No.)	PPR (kg C)
Skagerrak grid	8	11	21	1.3 ± 0.1	0.70 ± 0.1	0.5 ± 0.1	31 ± 6
Skagerrak conventional	8	12	22	1.2 ± 0.4	0.17 ± 0.1	3.2 ± 0.1	120 ± 37
Kattegat grid	5	12	23	2.5 ± 0.5	0.81 ± 0.2	1.0 ± 0.4	88 ± 22
Kattegat conventional	7	14	27	1.7 ± 0.3	0.75 ± 0.2	2.7 ± 0.6	89 ± 19

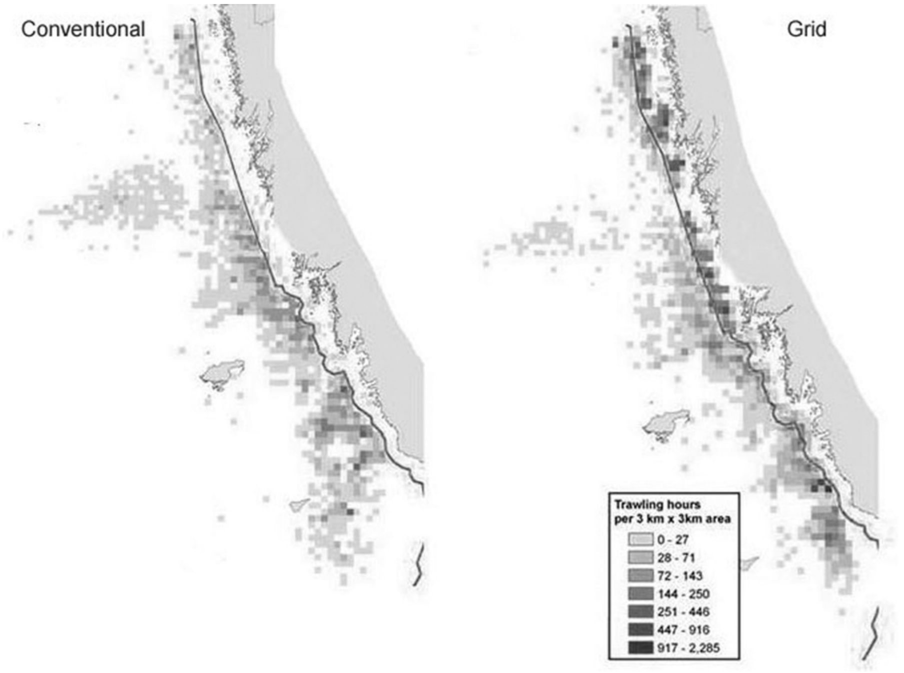

Fig. 5. Aggregated trawl effort for conventional (left) and grid trawling (right) in 2009.

10,000–22,000 m^2, with conventional trawling in the Skagerrak contributing to the lowest value and grid in the Kattegat twice the value.

Fuel consumption varied between 1.3 and 2.4 l of fuel consumed per kilogram of landings, with Skagerrak conventional trawling being the most energy-efficient practice and grid trawling needing nearly twice the amount per landing. These results were tested in a sensitivity analysis.

3.4. *Overall resource use and impact assessment results*

All inventory data and impact assessment results are presented in Fig. 6; inventory data, such as seafloor area swept and discards, are included in the same graph as these results are relevant without defining the potential impact. Conventional trawling generally used less fuel and disturbed less seafloor area per kilogram of landings than did grid trawling; however, grid trawling is superior in protecting threatened species.

3.5. *Sensitivity and uncertainty analysis*

3.5.1. *Change of functional unit*

If the aim is to keep the trawl fishery for *Nephrops* open, evaluating impacts per kilogram of landed *Nephrops* could be of interest. Choice of adequate general allocation method to share impacts and resource use between multiple outputs has been debated before [51,52], but, justified by the fact that conventional trawling targets the most profitable mix and grid trawling was developed to catch the economically important *Nephrops*, impacts are allocated between *Nephrops* and fish landings based on the percentage of total economic value (Fig. 7). Note that the remaining allocated figures for landed fish species should not be used separately.

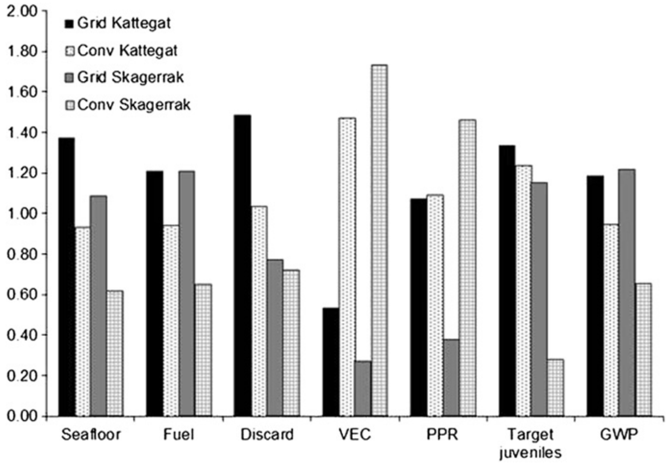

Fig. 6. Relative contribution (value of 1 is average of all practices) to mean levels of trawling impact for 1 kg of landings of the four fishing practices.

The dominant trawl practice in terms of contribution to *Nephrops* landings is single grid trawl in the Skagerrak area (28% of trawl landings). The new results indicated little if no tradeoffs per kilogram of *Nephrops* caught with grid, only fewer threatened fish caught and a lower PPR (Fig. 8).

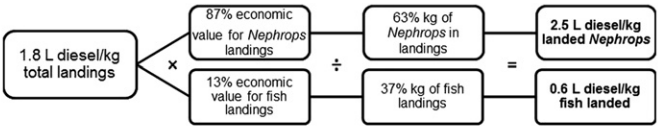

Fig. 7. Economic allocation in mixed fisheries; example taken from diesel use in conventional trawl fishery for *Nephrops* in Kattegat.

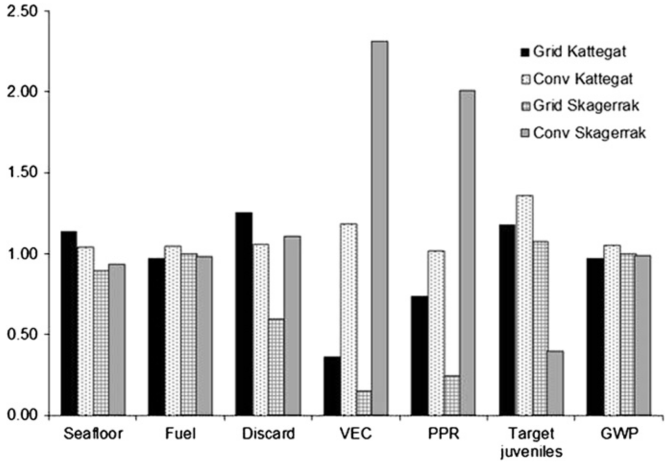

Fig. 8. Relative contribution (value of 1 is average of all practices) to mean levels of impact for landing 1 kg of *Nephrops* after economic allocation.

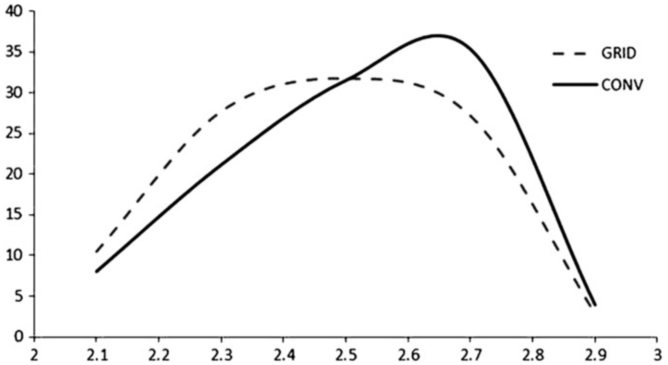

Fig. 9. Distribution in percent of vessel speed in knots for the two types of gear in the 2–3 knot interval.

Table 3
Likely direction of fuel use if it is not equal between types of gear; + = increase, – = decrease.

	Netting[a]	Depth[b]	Weight[c]	Location[d]
Grid	–	–	–	–
Conventional	+	+	+	+

[a] Grid uses a square mesh with better hydrodynamics.

[b] Grid is generally used in shallower areas due to optimization of gear performance.

[c] Grid has a lower total catch to be hauled.

[d] Grid trawling generally occurs closer to the coast.

3.5.2. Implications of differences between types of gear

The general assumption of an average speed of 2.5 knots was confirmed by analysis of VMS data. However, grid trawling, i.e., clean *Nephrops* trawling, would generally require less speed than fish trawling, and a slight difference in speed between the types of gear was also confirmed by VMS analysis (Fig. 9). This difference gives grid trawling a (not accounted for) lower seafloor area swept impact than that of conventional trawling, reducing originally assumed differences.

Differences in transportation distance assumed in the model did not significantly alter the final results. The higher speed of conventional trawling (Fig. 8) would increase the fuel consumption per effort. Other potential differences, such as, drag resistance and weight, would likely also contribute to grid trawling being more fuel efficient than conventional trawling (Table 3).

4. Discussion

Grid trawling complies well with management objectives, which are to reduce fishing mortality of cod. However, from a broader perspective, grid trawling has some tradeoffs and there are regional differences for the practice. Resource use in terms of fuel use per total landings is higher using grid trawls, approximately 1 l extra per kilogram landed, but this inefficiency is less important than the superior protection of threatened species contributed by grid practice. In addition, this study found that discard was highest in the Kattegat grid fishery; however, in terms of susceptibility to impact (VEC) and extent of disturbance (PPR), grid trawling is still superior to conventional trawling. Survival potential is also generally higher for discarded flatfishes and juvenile *Nephrops* than for the gadoid fish species discarded to a greater extent in conventional trawling. If the impacts are seen per kg of *Nephrops* landings (after economic allocation), no general elevated fuel use or seafloor impact is seen, suggesting that at present fish stock levels, grid trawling is not generating significant tradeoffs when targeting *Nephrops*; instead, it has a lower impact on threatened fish species and lower PPR. With the proposed discard ban in the upcoming reform of the EU Common Fisheries Policy, a selective practice such as grid trawling would be preferable, though it is important to be aware of compromises in other areas, such as fuel consumption.

By this study, it was demonstrated that LCA can be used to quantify potential tradeoffs from a management measure and to contrast regional effects (i.e., restoration of locally depleted fish stocks) to potential global effects (such as GHG emissions). Higher resolution of discard impacts was obtained by applying PPR and VEC to the discard mass.

4.1. Implications for fisheries managers

Integrated assessments should be carried out to ascertain the likely magnitude of the possible imposed tradeoffs and then determine priorities in order to mitigate the overall impacts of fisheries. LCA could quantify compliance with progress towards a good water quality status by 2020, as mandated by the EU Marine Water Directive [53]. Grid trawling would, in this context, probably be superior to the mixed fishery in terms of threatened species (descriptor 1), depletion of the populations of commercial fish species (descriptor 3), and trophic level distortions (descriptor 4). However, seafloor integrity (descriptor 6) is still relevant to grid trawling (a type of demersal trawling), which is allowed in areas protected from conventional trawling. As muddy habitats are important fishing grounds, they are often difficult to protect due to their economic value to fisheries. The trawling intensity of these habitats in coastal areas probably leaves few areas not permanently altered, making the protection of a few areas of biodiversity reserves important for replenishing the disturbed areas. The seafloor impact of grid trawling needs to be further addressed in the future.

The reform of the EU Common Fisheries Policy (CFP) [8] implies that ecology must be a top priority and a prerequisite for other sectors. However, social and economic consequences have traditionally had and will likely continue to have great influence in future CFP versions. Earlier findings have contrasted low GHG emissions from small vessels with high accident risk [54]. The grid construction, according to fishermen, is prone to higher accident risk and may become clogged. Separation of the two trawl practices is only economically viable due to the current large minimum landing size and associated market prices. The question is whether the top priority should be to subsidize selective trawling (to increase profit margin and security on board) or cut fossil fuel subsidies and reduce GHG emissions. It should also be noted that single-species fisheries driven by depletion from formerly fished stocks could incur increasing risks, in terms of both production stability and profits [55]. As present fish stock levels in the area do not allow a sustainable mixed fishery, it could be questioned why the trawling fleet should continue to catch a mainly luxury food item when creeling is an alternative with considerably less associated impact [22].

4.2. Implications for LCA methodology

The former LCA study [22] of trawled *Nephrops* identified higher fuel consumption than was found here. First, a different approach to modeling was used and the system boundaries were set differently; for example, the former study used sample fuel data covering yearly fuel use instead of modeling the whole fleet, aggregated Kattegat and Skagerrak, and using a different definition of the *Nephrops* fleet. Second, data from all demersal fisheries in Sweden indicate a trend towards decreased fuel consumption of approximately 40% per landing from 2003 to 2008 [56]. The data in [22] was from 2004 which according to [56] was the highest in terms of fuel use. In addition, *Nephrops* catches in 2009 were relatively high at 1334 t, whereas in 2004 – the year of the earlier study – only 906 t of *Nephrops* were landed, leading to relatively high fuel consumption. This indicates limitations of snapshot studies. Earlier findings derived from examining longer periods indicate great between-year differences in pelagic fisheries [57], making different studies difficult to compare. Absolute values for fuel use are not only depending on which approach used, but could also be sensitive to boat sizes in sample data and which transportation scenarios chosen (e.g. speed, length), as it recently was shown that the fuel need derived from this study might be a bit optimistic (Ziegler and Hornborg, in preparation).

This study also demonstrates that accounting only for discard quantity in LCA is a rough measure of impact on the marine ecosystem. Although total discard quantity is high, differences in species composition may imply that the result is not as serious as initially appears. Accordingly, the discard indicators chosen in this study increasingly identify potential environmental effects of fisheries than simply total discard quantity. However, one area of concern for VEC is the divergent perspectives of conservation biology and fisheries management. The lowest decline rate of a species to fall under the IUCN Red List threatened species criteria is a population reduction of 50% in ten years or three generations. The same decline rate could according to management objectives be a fully sustainable exploitation, as the theoretic biomass at maximum sustainable yield (B_{MSY}) is in general at 50% reduction of natural biomass [58]. Possible discrepancies between sustainable natural resource exploitation and adverse effects need to be further addressed in terms of the biological impacts of fisheries however, congruent assessments from both perspectives have been found in the area of study (Hornborg et al., in preparation). In terms of the PPR of discards, LCA can provide interesting insights. Trawling for Norway lobster can be compared to salmon aquaculture in terms of acquisition of primary production. Discards acquire 31–260 kg C per kilogram of *Nephrops* (economic allocation), equivalent to or even higher than the appropriation from feed in salmon culture, i.e., 18–137 kg C per kilogram of live-weight salmon [59]. The results indicate that discard is a hidden cost of fisheries, making use of PPR as a sustainability tool interesting if cautions are made on which data sources and historical time frame that are used (Hornborg et al., in preparation). According to estimated %PPR from landings in relation to availability [60], the North Sea area was found to have a 40% probability of being sustainably fished, making accounting for PPR in fisheries important, though further elaboration of the implications, in terms of impact, of different PPR levels is recommended.

5. Conclusions and future recommendations

Species-selective trawling for *Nephrops* fulfils the objectives for fish by-catch management in the area; however, from a broader perspective, it is more resource intensive than conventional trawling in terms of fuel use and seafloor disturbance per landed kilo. Still, per kg of *Nephrops* (after economic allocation), grid trawling is superior in terms of threatened species affected while being equal in fuel use. Using LCA, the seafood industry can be made more transparent and potential tradeoffs in resource use and environmental impacts can be identified to facilitate improvements and better resource use. Future modeling of the implications of primary production requirements, threatened species impact, and target stock long-term wastage would improve the results.

More data of greater detail are needed to increase the accuracy of assessments. A study linking vessel size and fish mortality in Danish fisheries suggested a logarithmic increase for gear size [61]; this would be interesting to study in greater detail, as no data were available on individual trawl width. Less secrecy regarding fuel consumption in fisheries would also foster improvement.

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References

[1] Degnbol PH, Gislason H, Hanna S, Jentoft S, Raakjær Nielsen J, Sverdrup-Jensen S, et al. Painting the floor with a hammer: technical fixes in fisheries management. Mar Policy 2006;30:534–43.
[2] Worm B, Barbier EB, Beaumont N, Duffy JE, Folke C, Halpern BS, et al. Impacts of biodiversity loss on ocean ecosystem services. Science 2006;314:787–90.
[3] Mora C, Myers RA, Coll M, Libralato S, Pitcher TJ, Sumaila RU, et al. Management effectiveness of the world's marine fisheries. PLoS Biol 2009;7:e1000131. http://dx.doi.org/10.1371/journal.pbio.1000131.
[4] Worm B, Hilborn R, Baum JK, Branch TA, Collie JS, Costello C, et al. Rebuilding global fisheries. Science 2009;325:578–85.
[5] Arnason R, Kelleher K, Willmann R. The Sunken Billions: The Economic Justification For Fisheries Reform. World Bank and FAO; 2008.
[6] Jackson JBC. The future of the oceans past. Philos Trans R Soc B: Biol Sci 2010;365:3765–78.
[7] Rome: FAO; 2010.
[8] Green Paper: Reform of the Common Fisheries Policy. Commission of the European Communities, Brussels 22.4.2009.

[9] SEA Directive 2001/42/EC.
[10] Environmental management: life cycle assessment – Principles and framework. ISO 14040:2006(E). International Organization for Standardization. Geneva. Switzerland. and Environmental Management: Life Cycle Assessment – Requirements and Guidelines. ISO 14044:2006(E). International Organization for Standardization, Geneva, Switzerland.
[11] Thrane M. LCA of Danish fish products. New methods and insights. Int J Life Cycle Assess 2006;11:66–74.
[12] Ziegler F Environmental life cycle assessment of seafood products from capture fisheries. PhD Thesis, Göteborg University, Department of Marine Ecology/SIK, The Swedish Institute for Food and Biotechnology. 2006, SIK report 754.
[13] Standal D. Nuts and bolts in fisheries management: a technological approach to sustainable fisheries? Mar Policy 2005;29:255–63.
[14] Utne IB. System evaluation of sustainability in the Norwegian cod fisheries. Mar Policy 2007;31:390–401.
[15] Hospido A, Tyedmers P. Life cycle environmental impacts of Spanish tuna fisheries. Fish Res 2005;76:174–86.
[16] Driscoll J, Tyedmers P. Fuel use and greenhouse gas emission implications of fisheries management: the case of the New England Atlantic herring fishery. Mar Policy 2010;34:353–9.
[17] McClenachan L. Documenting loss of large trophy fish from the Florida keys with historical photographs. Conserv Biol 2009;23:636–43.
[18] Pauly D, Christensen V, Dalsgaard J, Froese R, Torres Jr. F. Fishing down marine food webs. Science 1998;279:860–3.
[19] Pauly D. Anecdotes and the shifting baseline syndrome of fisheries. Trends Ecol Evol 1995;10:430.
[20] Watling L, Norse EA. Disturbance of the seabed by mobile fishing gear. CompFor Clearcutting Conserv Biol 1998;12:1180–97.
[21] Pelletier N, Ayer N, Tyedmers P, Kruse S, Flysjo A, Robillard G, et al. Impact categories for life cycle assessment research of seafood production systems: review and prospectus. Int J Life Cycle Assess 2007;12:414–21.
[22] Ziegler F, Valentinsson D. Environmental life cycle assessment of Norway lobster (*Nephrops norvegicus*) caught along the Swedish west coast by creels and conventional trawls. LCA methodology with case study. Int J Life Cycle Assess 2008;13:487–97.
[23] Chassot E, Bonhommeau S, Dulvy NK, Melin F, Watson R, Gascuel D, et al. Global marine primary production constrains fisheries catches. Ecol Lett 2010;13:495–505.
[24] Gärdenfors U Manual och Riktlinjer för Rödlistning i Sverige 2010. ArtDatabanken, 2010.
[25] Dulvy NK, Jennings S, Goodwin NB, Grant A, Reynolds JD. Comparison of threat and exploitation status in North-East Atlantic marine populations. J Appl Ecol 2005;42:883–91.
[26] Mace GM, Collar NJ, Gaston KJ, Hilton-Taylor C, Akcakaya HR, Leader-Williams N, Milner-Gulland EJ, Stuart SN. Quantification of extinction risk: IUCN's system for classifying threatened species. Conserv Biol 2008;22:1424–42.
[27] ICES advice 2010, Book 6.
[28] Kelleher K Discards in world's marine fisheries, an update. FAO. 2005, Fisheries Technical Paper:131 p.
[29] Valentinsson D, Ulmestrand M. Species-selective *Nephrops* trawling: Swedish grid experiments. Fish Res 2008;90:109–17.
[30] EC Council Regulation 423/2004.
[31] EC Council Regulation 1342/2008.
[32] EU Council Regulation 754/2009.
[33] Madsen N, Valentinsson D. Use of selective devices in trawls to support recovery of the Kattegat cod stock: a review of experiments and experience. ICES J Mar Sci: JConseil 2010;67:2042–50.
[34] Rogers A.D. and Laffoley Dd'A. International Earth system expert workshop on ocean stresses and impacts. Summary Report 2011. IPSO Oxford, 18 pp.
[35] Ellingsen H, Olaussen JO, Utne IB. Environmental analysis of the Norwegian fishery and aquaculture industry: a preliminary study focusing on farmed salmon. Mar Policy 2009;33:479–88.
[36] Vázquez-Rowe I, Moreira MT, Feijoo G. Life cycle assessment of horse mackerel fisheries in Galicia (NW Spain): comparative analysis of two major fishing methods. Fish Res 2010;106(3):517–27.
[37] Peacock N, De Camillis C, Pennington D, Aichinger H, Parenti A, Rennaud J-P, et al. Towards a harmonised framework methodology for the environmental assessment of food and drink products. Int J Life Cycle Assess 2011;16(3):189–97.
[38] Magerholm Fet A, Schau EM, Haskins C. A framework for environmental analyses of fish food production systems based on systems engineering principles. Syst Eng 2010;13:109–18.
[39] Suuronen P Mortality of fish escaping trawl gears. 2005; FAO Fisheries Technical Paper 478.
[40] Bastardie F, Nielsen JR, Andersen BS, Eigaard OR. Effects of fishing effort allocation scenarios on energy efficiency and profitability: an individual-based model applied to Danish fisheries. Fish Res 2010;106:501–16.
[41] Parente J, Fonseca P, Henriques V, Campos A. Strategies for improving fuel efficiency in the Portuguese trawl fishery. Fish Res 2008;93:117–24.
[42] Nilsson P, Ziegler F. Spatial distribution of fishing effort in relation to seafloor habitats in the Kattegat, a GIS analysis. Aquat Conserv: Mar Freshwat Ecosyst 2007;17:421–40.
[43] Ziegler F, Emanuelsson A, Eichelsheim JL, Flysjö A, Ndiaye V, Thrane M. Extended life cycle assessment of southern pink shrimp products originating in Senegalese artisanal and industrial fisheries for export to Europe. J Ind Ecol 2011;15(4):527–38.
[44] Ellingsen H, Aanondsen SA. Environmental impacts of wild caught cod and farmed salmon: a comparison with chicken. Int J Life Cycle Assess 2006;1(1):60–5.
[45] Intergovernmental panel on climate change, Fourth Assessment Report 2007. The Physical Science Basis.
[46] Pelletier N, Tyedmers P. Feeding farmed salmon: is organic better? Aquaculture 2007;272:399–416.
[47] Pauly D, Christensen V. Primary production required to sustain global fisheries. Nature 1995;374(6519):255–7.
[48] ICES advice for 2012, Book 6, Chap 6.4.13.
[49] Ulmestrand M, Eggert H. Growth of Norway lobster, *Nephrops norvegicus* (Linnaeus 1758), in the Skagerrak, estimated from tagging experiments and length frequency data. ICES J Mar Sci 2001;58:1326–34.
[50] Castro M, Araújo A, Monteiro P, Madeira AM, Silvert W. The efficacy of releasing caught *Nephrops* as a management measure. Fish Res 2003;65(1–3):475–84.
[51] Svanes E, Vold M, Hanssen J. Effect of different allocation methods on LCA results of products from wild-caught fish and on the use of such products. Int. J. Life Cycle Assess 2011;16:512–21.
[52] Pelletier N, Tyedmers P. An ecological economic critique of the use of market information in life cycle assessment research. J Ind Ecol 2011;15(3):342–54.
[53] EU directive 2010/232/14.
[54] Utne IB. Are the smallest fishing vessels the most sustainable? Trade-off analysis of sustainability attributes Mar Policy 2008;32(3):465–74.
[55] Steneck RS, Hughes TP, Cinner JE, Adger WN, Arnold SN, Berkes F, et al. Creation of a gilded trap by the high economic value of the maine lobster fishery. Conserv Biol 2011;25(5):904–12.
[56] European Commission Joint Research Centre. The 2010 Annual Economic Report on the European Fishing Fleet. JRC Scientific and Technical Reports 2010.
[57] Ramos S, Vázquez-Rowe I, Artetxe I, Moreira MT, Feijoo G, Zufía J. 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 2011;16:599–610.
[58] Reynolds J.D., Dulvy N.K., Goodwin N.B., Hutchings J.A. Biology of extinction risk in marine fishes. Proc R Soc B: Biol Sci 2005; 272:2337–2344.
[59] Pelletier N, Tyedmers P, Sonesson U, Scholz A, Ziegler F, Flysjo A, et al. Not all salmon are created equal: life cycle assessment (LCA) of global salmon farming systems. Environ Sci Technol 2009;43(23):8730–6.
[60] Coll M, Libralato S, Tudela S, Palomera I, Pranovi F. Ecosystem overfishing in the ocean. Plos One 2008:3.
[61] Eigaard OR, Rihan D, Graham N, Sala A, Zachariassen K. Improving fishing effort descriptors: modelling engine power and gear-size relations of five European trawl fleets. Fish Res 2011;110:39–46.