Evaluating Fisheries Management from a Life Cycle Perspective with New Approaches to By-catch Impacts

Sara Hornborg

Licentiate thesis
Department of Biological and Environmental Sciences
University of Gothenburg
Evaluating fisheries management from a Life Cycle perspective with new approaches to by-catch impacts

Sara Hornborg
Licentiate thesis

Keywords: LCA, fisheries management, red listed fish species, trophic indicators

© Sara Hornborg, 2012
 Sustainable Food Production, Swedish Institute for Food and Biotechnology (SIK)
 Department of Biological and Environmental Sciences, University of Gothenburg, Sweden
 Printed by Kompendiet, Aidla Traiding AB, Gothenburg, Sweden 2012
 ISBN: 91-89677-50-1
The licentiate seminar will be held at 10.00 on the 26th of April, 2012, at the Department of Biological and Environmental Sciences in Gothenburg (Botan, Carl Skottsbergs gata 22).

External reviewer: PhD Henrik Österblom, Stockholm Resilience Center, Stockholm University

Supervisors: PhD Friederike Ziegler (main), Sustainable Food Production, the Swedish Institute for Food and Biotechnology (SIK)

Assoc. Prof. Per Nilsson, Department of Biology and Environmental Sciences, University of Gothenburg

PhD Daniel Valentinsson, Department of Aquatic Resources, Swedish University of Agricultural Sciences, Lysekil

Examiner: Professor Kristina Sundbäck, Department of Biology and Environmental Sciences, University of Gothenburg
Till mina älskade barn Elias och Ella

För Framtida Fina Fiskpinnar
Abstract

Life cycle assessment (LCA) couple resource use and environmental impacts attributed to a product during its life cycle. Method development is still needed to better quantify (in the case of seafood) impacts on target stock, by-catch and seafloor disturbance. The present thesis focuses on improved assessment of unintentional catches in LCA, and suggests two complementary methods to assess their impacts: primary production required (PPR, in mass of carbon accumulated per kilo wet weight of a species at a certain trophic level) and the amount of red listed fish species (VEC, in mass or number) in discards per kilo of seafood product.

Based from the results from studying Swedish fisheries landings in comparison to survey data, onboard monitoring of discards and data on primary production from the Kattegat and Skagerrak during the last century, quantifying PPR from discards is suggested as a differentiated seafood product impact. Different gears and targeting patterns varied greatly in terms of PPR from the discarded part of the catch, additionally shown for the mean trophic level (MTL) of catch, landing and discard. Even if this show that different seafood products can be attributed different PPR, the interpretation in terms of impact from having different PPR values must be made with caution. PPR must be placed in a historical context, as well as it is necessary with complementing information on impact on depleted stocks, susceptible to further impacts from discards.

As it was additionally found that the Swedish national IUCN red list of marine fish species showed high consistency with scientific advice, as well as sensitive life history traits, quantifying the amount of threatened fish species in discards (VEC) showed to be an appealing complementing indicator for the sensitivity of different discard compositions. In discard data from the demersal trawl fisheries in the Kattegat and Skagerrak, differences in amount of VEC per kilo of landing were found between fleet segments targeting different species. By this, it is suggested that VEC could be used as a carrier of aggregated information of the susceptibility of the impact to be included within the LCA framework.

The resource use and environmental impacts of a seafood product is strongly linked to fisheries management (e.g. gear regulations, effort restrictions and quotas), as prior LCA’s of capture fisheries have been found to in general be dominated by the fishing phase. By using a life cycle approach to the management of the Norway lobster (*Nephrops norvegicus*) trawl fisheries in the Kattegat and Skagerrak area, LCA was tested as a new tool to optimize marine resource use in a broader perspective. With the new approaches to discard assessment applied, it was found that from a product perspective, protecting locally depleted fish stocks in the area comes with a trade-off in e.g. seafloor area swept and fuel use. Fisheries management needs to consider that both fish and fossil fuel resources are presently scarce, which makes an integrated perspective of increasing importance to create an overall sustainable resource use.

In the case study, it was additionally found that assessing discards in LCA by combining PPR and VEC, enhance the picture of varied discard impact depending on species composition. Still, further method development is needed regarding impacts on target stocks and differentiated seafloor impacts.
Svensk sammanfattning

Hur kan man koppla en fisk- och skaldjursprodukt till dess breda miljöpåverkan och använda denna information för till exempel produktrelaterad information? Ett sätt är att använda livscykelanalys (LCA), en metod som beräknar allt resursutnyttjande och all miljöpåverkan längs med en produkts livscykel, ofta i ett ”vaggan-till-graven-perspektiv”. På så vis kan man jämföra olika produkters miljöpåverkan, som skillnader mellan t.ex. glas- och plastflaskor, växthusodlade och frilandsodlade grönsaker; eller identifiera förbättringspotentialer inom produktionsprocess som skillnader mellan olika fodersammanställningar inom laxodling.

Eftersom LCA som metod är relativt ny har den brister vad gäller att inkludera biologisk miljöpåverkan, och fokus har oftast varit på bränslebehovet. Tidigare livscykelanalys av fisk- och skaldjursprodukter har visat att miljöavtrycket varierar stort mellan olika fängstmetoder inom fisket. För att dock kunna genomföra en så heltäckande utvärdering av fiskets miljöpåverkan som möjligt behövs metodutveckling, för fisk- och skaldjursprodukter främst för påverkan av målart, bifångster och bottenyta.

Fiskets miljöpåverkan genom oönskade fångster föreslås att skattats på två olika sätt: antalet hotade fiskar (rödlistade) och det s.k. primärföreningsskapet som behövts för att producera ett kilo av en art beroende på placering i näringskedjan) i den del av fångsten som kastas i relation det som säljs (landas). Dessa två metoder testas i en fallstudie av svensk trålning efter havskräfta (studie I) samt diskuteras i två separata mer metodinriktade studier (II & III).

Användning av trofiska mätpunkter inom fisket (studie III)


I studie III utvärderades svenskt landningsdata från Kattegatt och Skagerrak under det senaste århundradet vad gäller medeltrofinivån och primärföreningsskapet. Resultatet jämfördes med data från provfiske och högupplöst data som även inkluderade den bortkastad delen av fångsten i ett antal Trälfiske höga fiskerier, samt halter av primärförening. Studien visar att redskapsrelaterad och fiskeinriktning markant påverkar båda dessa indikatorer, och att det var viktigt att titta även på den kastade delen av fångsten. Blandträlssfiske efter fisk och kräfta kan till exempel ha enbart fem procent av sitt totala primärföreningsskapet från den landade delen av fångsten, medan renare bottenträlssfiske efter fisk har motsvarande över åttio procent. Detta gör indikatorerna lämpliga för att utvärdera skillnader i påverkan mellan olika fiskemetoder inom ett område och över tid, speciellt genom att titta på den bortkastade delen,
och mindre lämplig på global nivå. Det är dock viktigt att känna till områdets historia för att kunna säga något om skadepotential, speciellt för fiskets primärproduktionsbehov som visade sig ha minskat över tid i förhållande till tillgänglig primärproduktion, samt komplettera informationen med uppgifter om påverkan av överexploaterade fiskbestånd.

Rödlistade fiskarter som indikatorer för påverkan från oönskad fångst (studie II)

Hoten mot rödlistade fiskarter är ofta starkt kopplade till överexploatering genom fiske. De arter som historiskt har fått mest uppmärksamhet som bifångst är marina däggdjur, fåglar och sköldpaddor, medan uppmärksamheten är generellt lägre kring fiskarter med samma hotbild.

I studie II utvärderades den svenska rödlistningen av fiskar i relation till förvaltningens rådgivning samt till egenskaper hos fisk som är känsliga för fisketryck (stor maxlängd, hög maxålder och hög ålder vid könsmognad). Rödlistans klassificering av fiskar i Sverige visade sig stämma väl överens med de övriga skattningarna av känslighet för fisketryck som testades i studien. Genom att studera mängd eller massa rödlistade fiskarter i den kastade delen av fångsten i förhållande till den använda delen visade det sig att denna andel skiljer sig mellan olika typer av redskap i området. Utöver icke hotade arter, kastade blandtrålsfisket inriktat mot havskräfta störst andel hotade fiskarter per landat kilo, runt trettio exemplar för varje tio landade kilon, medan artsselectiv tråling efter räka endast genererade en hotad fiskart kastad per tio kilo landning. Som LCA-tillämpning för att skatta oönskade fångsters påverkan av känsliga arter från en fisk- eller skaldjursprodukt, föreslås därmed att skatta hur mycket rödlistade fiskar som kastas bort i förhållande till varje kilo som tas iland. Denna information kan ses som en sammanvägd bild av känsliga egenskaper och grad av överfiske.

Utvärdering av förvaltningen av trålfisket efter havskräfta i Sverige (studie I)


Studien visar att miljöpåverkan från tråling efter havskräfta varierar stort beroende på redskap och område. Artsselectiv bottentråling efter havskräfta skyddar kraftigt överfiskade fiskbestånd, men på bekostnad av ökat bränslebehov (och därmed ökade utsläpp av växthusgaser). Det ger också en större bottenfia påverkad per kilo landning. Genom denna
sammanvägda bild av miljöpåverkan från ett förvaltningsbeslut får man ett mer integrerat underlag kring aspekter som vid beslutsfattandet låg utanför förvaltningens direkta åtagande. Följaktligen uppstår en motsättning mellan en förvaltningsåtgärd för att skydda lokala torskbestånd och det globala perspektivet, eftersom åtgärden medför ett ökat behov av fossila bränslen och ökade växthusgasutsläpp per kilo landning.

**Slutsatser**

Genom att bättre kunna skatta påverkan från att kasta en del av fångsten kan man med miljösystemanalys som LCA bättre undvika att bortse ifrån viktiga aspekter av miljöpåverkan på grund av avsaknad av metod. Primärproduktionsbehovet belyser en viktig aspekt, men säger ingenting om huruvida en påverkad art är vanlig, sällsynt, ökar eller minskar. Förekomsten av hotade arter säger å andra sidan ingenting om resursbehovet. En kombination av skattning av båda två i den oönskade delen av fångsten ger en mer initierad bild av miljöpåverkan från den bortkastade delen av fångsten. På så sätt ges möjligheter till mer heltäckande produktrelaterad information samt bredare utvärderingar av fiskeriförvaltning för att skapa ett mer integrerat underlag för beslutsfattning för ett mer hållbart resursutnyttjande. Fortsatt metodutveckling för att inkludera påverkan på målart och botten rekommenderas för att ytterligare stärka LCA som förvaltningsverktyg och möjliggöra jämförelser mellan olika fisk- och skaldjursprodukters bredare miljöpåverkan.
Acknowledgements

First, I am of course greatly in debt to my knowledgeable and overall fantastic supervisors. Friederike, your sharp brain does not miss a thing and you are always extremely supporting and encouraging! Daniel and Per, your long experiences from fisheries management and conservation planning have contributed to many extremely interesting discussions and insights.

I would also like to thank my co-PhD-colleague Andreas Emanuelsson, for interesting discussions and supporting words. Also, the rest of our project group, Leif Pihl (GU) and Mattias Sköld (SLU), it is always a treat when we all get together. The same goes for my department at SIK, Sustainable Food Production, for hearty and inspiring coffee breaks, sustainable food production can never be a boring topic! Cheila (Portuguese “sardine-hugger”) and Veronica (miss Eco-label), extra dear colleagues in the field of sustainable seafood!

Katja Ringdahl for providing and assisting with data, not to mention all the patience with all the questions that I have had! Mikael Svensson at ArtDatabanken, for interesting discussions and invaluable data. Andrea Belgrano and Valerio Bartolino, for discussing and commenting on paper III. Kristina Sundbäck, thank you for taking care of all practicalities in the role of examiner.

All friends in Göteborg that have lightened up the little spare-time I have had in recent years: Malin, Mia, Robin, Tea, Björn, Lena, Lars, Sara, and more…and all others up the west coast (Erica, Andreas, Malin K, Håkan, Kalle, Marie, Fredrik…) even if a quick car ride outside town has been sadly rare in recent years, it is always great when we meet. Thank you all for support and inspiration!

Last, but certainly not least, my little family with my ever supporting husband Totte, “up-and-coming-marine-biologist” -Elias and “ever-happy-and-full-of-jokes” -Ella. Linnéa, for helping me keeping it all together and keeping me in contact with the world outside fisheries, such as the latest music and fashion (and for taking care of my physical training 😊). You all form the base to my existence.

Thank you all!

Sara
The thesis is based on the following list of papers:

http://dx.doi.org/10.1016/j.marpol.2012.02.017  
*In press. Reprinted with kind permission, copyright of Elsevier.*

**Paper II**  Hornborg, S., Svensson, M., Nilsson, P. & Ziegler, F. Use of red listed fish species as indicators for fishing by-catch impact on sensitive species. *Manuscript*

**Paper III**  Hornborg, S., Belgrano, A., Bartolino, V., Valentinsson, D. & Ziegler, F. Mean Trophic Level and Primary Production Required in Swedish fisheries over a century: prospects and limitations of the indicators. *Manuscript*
Table of contents

Definitions and abbreviations

1. Aim
2. Methods and data used
   2.1 Methods
   2.2 Data
3. Introduction
4. Life Cycle Assessment and seafood production
   4.1 General LCA methodology
   4.2 LCA of capture fisheries
   4.3 Fuel use in Swedish Nephrops trawl fisheries
5. Environmental impacts of capture fisheries
   5.1 Target catch
   5.2 Unintentional catches: By-catch and discard
      5.2.1 Non-commercial species in discards
      5.2.2 Discard of commercial species
   5.3 Benthic impacts
6. New approaches to by-catch assessments
   6.1 Threatened species
   6.2 Food web interactions
7. Fisheries management and LCA
8. Conclusions and future outlook

References

Paper I
Paper II
Paper III
### Definitions and abbreviations

**By-catch**
The part of the catch that is not directly targeted consisting of two parts: one that is utilized, but most lack sufficient management due to data deficiency; one that is discarded at sea, could be undersized, quota filled species or non-commercial species, not recorded in logbooks.

**Discard**
The part of the catch in a fishery that is thrown away at sea and only recorded in onboard monitoring programs. This could be non-commercial fish- and invertebrate species, but also juveniles of target species, quota restricted marketable species or marketable species with lower economic value that the fishing preference (high-grading).

**CBD**
Convention of Biological Diversity

**CPUE**
Catch per unit effort

**CITES**
Convention on International Trade in Endangered Species of Wild Fauna and Flora

**EBFM**
Ecosystem Based Fisheries Management

**GHG**
Greenhouse Gas

**HCFC/HFC**
Hydrochlorofluorocarbon/ Hydrofluorocarbons (freons)

**ICES**
International Council for the Exploration of the Sea, scientific community with participants from all states bordering the North Atlantic and the Baltic Sea.

"... co-ordinates and promotes marine research on oceanography, the marine environment, the marine ecosystem, and on living marine resources in the North Atlantic."

**IPCC**
Intergovernmental Panel on Climate Change

**IUCN**
International Union for Conservation of Nature

**Landings**
The part of the catch that is recorded in logbooks and brought to market.

**LCA**
Life cycle assessment

**MTL**
Mean trophic level

**PPR**
Primary production required
<table>
<thead>
<tr>
<th><strong>RLI</strong></th>
<th>Red list index</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TAC</strong></td>
<td>Total Allowable Catch, the maximum allowed amount of a certain stock to be landed per year. The concept is confounding as it is not referring to catch, but landing, i.e. not including discards.</td>
</tr>
<tr>
<td><strong>TE</strong></td>
<td>Transfer efficiency</td>
</tr>
<tr>
<td><strong>TL</strong></td>
<td>Trophic level</td>
</tr>
<tr>
<td><strong>VEC</strong></td>
<td>Vulnerable, Endangered or Critically Endangered (according to IUCN criteria)</td>
</tr>
</tbody>
</table>
1. Aim

The aim of this thesis is two-fold:

- To establish a framework for assessing important biological impacts from unintentional catches in capture fisheries for use in e.g. Life Cycle Assessment (LCA) studies.
- Use the expanded LCA as a tool for evaluation of the broader environmental impacts of decisions in fisheries management.

2. Methods and data used

2.1 Methods

Life cycle assessment (LCA) is a method to couple all resource use and environmental impacts of relevance to an entity of focus, a functional unit, often with a “cradle-to-the-grave”-perspective. In paper I, a form of LCA called “life cycle thinking” was used to study the most important phase in the lifecycle of a seafood, the fishing phase, in order to assess the importance of fisheries management for the outcome of a product from capture fisheries, as well as testing new approaches to assess potential impacts from by-catch within the LCA framework. The functional unit of the study was one kg of mixed landed seafood from the Swedish Norway lobster (*Nephrops norvegicus*) trawl fishery, in terms of mean values for one year (2009). Impacts considered were discards (total mass, juveniles of target stock, primary production required and threatened species affected); seafloor area swept; fuel use and greenhouse gas emissions; and a qualitative discussion about the impact on the target stock. Important to note is that the impacts are only considered at the level of “potential to cause impact”, not “effect”.

In paper II, the consistency of the red listing of marine fish species in Sweden (with guidelines provided by the International Union for Conservation of Nature (IUCN) at iucnredlist.org) was assessed in relation to scientific advice on stock status and data on life history traits that have prior been found to indicate sensitivity to fishing pressure. The amount of threatened fish species (individuals, mass and number of species) was further studied in the discard composition of demersal trawl segments in the Kattegat and Skagerrak area. The intent with this study was to evaluate the robustness and possibilities of using red listed fish species in discards as indicators for the seafood product’s impact on sensitive and overexploited fish species, to be used for communication (e.g. LCA) and fisheries management evaluation.

In paper III, estimates on primary production required (PPR; model from Pauly & Christensen, 1995) as well as mean trophic level (MTL; model from Pauly et al., 1998) of landings, catch, discard and survey data from the Kattegat and Skagerrak was made. As trophic indicators are at present used in several disciplines, the approach in this paper was to contribute to the understanding of limitations, as well as possibilities, of using the indicators for various purposes.
2.2 Data

The data used for all three studies were:

- Swedish fisheries landings during 1903-2010 (available at www.ices.dk)
- Survey data from the 1970s from the International Bottom Trawl Survey (IBTS) coordinated by the International Council for Exploitation of the Seas (ICES) and available at www.ices.dk.
- Data on discards for one year (2009; 167 hauls) from sampling by trained scientific observers from the Department of Aquatic Resources (Institute of Marine Research, Swedish University of Agricultural Sciences) in accordance with the Data Collection Framework (DCF; EC Council Reg 199/2008).
- Primary production data came from the Swedish Meteorological and Hydrological Institute (www.smhi.se), sampled during 1985-2010.
- Fuel use was based on a model derived from Danish fisheries by Bastardie et al. (2010) which was applied on Swedish logbook data from one year (2009) on effort, kW and landings; adjusted from interviews with fishermen in the studied segments (12 boats landing approximately 25% of the Nephrops trawl landings).
- Life history traits and threat status was provided by the Swedish Species Information Centre (ArtDatabanken, www.slu.se).
- Scientific advice on stock status was taken from ICES (www.ices.dk).
- Trophic level of fish species was taken from www.fishbase.org; trophic level of invertebrates from www.seaaroundus.org.
- Combustion figures for greenhouse gas emissions from diesel use came from Swedish Petroleum & Biofuel Institute (www.spbi.se)
- Area impacted by trawl was based on a model derived from a study in the same area in Nilsson & Ziegler (2007) and applied on one year (2009) of logbook data on effort, trawl type and landings.
3. Introduction

The history of marine resource use is a sad story (Roberts, 2007). It is easily forgotten what the diversity and size of fish used to be (Jackson, 2001), as former abundances are increasingly distant and we now only have pictures left to be amazed at (Pauly, 1995; McClanachan, 2009). Former exploitation patterns, as well as its effects, can also be seen in statistics, such as the Swedish landings of Atlantic Bluefin tuna (*Thynnus thynnus*) that appeared in landing statistics in the Kattegat and Skagerrak area in the 1930s (Figure 1).

![Figure 1. Swedish landings of Bluefin tuna (*Thynnus thynnus*) in the Kattegat and Skagerrak area. Data for the 60s and early 70s are missing due to landings being aggregated with the North Sea. The last landing was 1 ton in 1991.](image)

Bluefin tuna was before this regional depletion an ecologically important top predator in the North Sea ecosystem for 2-3 months per year (MacKenzie & Myers, 2007). The history of exploitation of this species is only one in the line of repeated local depletions of stocks (Jackson *et al*., 2001). In fact, the last century’s increase in global landings has only been enabled from expansion of fishing grounds, with the greatest expansion during the 1980s-early 1990s, followed by a decline of newly exploited areas coinciding with a decline in global fish landings (Watson & Pauly, 2001; Swartz *et al*. 2010).

To mitigate the negative effects from the competitive nature of fisheries, management of fisheries has evolved. Politicians set quotas based on scientific advice after undergoing a political negotiation process between countries with interests in the fishery. This protection of marine resources by governmental authorities took off quite late in the history of fisheries exploitation, with Beverton and Holt (1957) providing the initial fundamental theory for optimum resource use. Their models have been heavily debated since then, revisited and revised (Larkin, 1977; Mace, 2001).

Management of a natural resource is not straightforward. The definition of success and failure of fisheries management can be seen from different perspectives. The ideal resource use would be to have the highest maximum long-term output of fish production to human use without causing adverse effect on ecosystem structure and functioning, provided this at all can be defined. In reality, politics (*i.e.* economics) have played a major role, resulting in single species overexploitation and less respect to ecological consequences (MacKenzie & Myers,
2007) or the scientific advice (Cardinale & Svedäng, 2008). The somewhat narrow focus of fisheries managers, has in general failed to acknowledge the complexity of natural resource use and the interactions of several disciplines such as biology, economics and sociology (Browman & Stergiou, 2004; Degnbol et al., 2006), further complicated by insufficient data reporting (Agnew et al., 2009; Zeller et al., 2009).

With anthropogenically driven climate change from combustion of fossil fuels is now established (Solomon et al., 2009) as well as increasing evidence of peak oil having been passed (Aleklett, 2010), it is important to put energy use in fisheries further up on the agenda, especially due to the energy intensity in many fisheries (Tyedmers et al., 2005; Ziegler, 2006; Thrane, 2006; Iribarren et al., 2010) and important interactions between climate change and production of seafood (Rice et al., 2011). Dependency on cheap fossil fuel and greenhouse gas emissions from the fishing fleet cannot be neglected for much longer, but how could it be integrated side by side with other fisheries management considerations?

Meanwhile, the global trend of fish consumption per capita is increasing (FAO, 2010). With health policies promoting increased fish consumption, optimizing marine capture production is increasingly essential (Brunner et al., 2009). As a response to the noticeable failures of management, increased consumer awareness has evolved which create incentives for eco-labeling of seafood products (FAO, 2010). Eco-labeling offers easy-to-grasp information to the consumer saying “good” and has shown to have led to some environmental improvements (MSC, 2011a) even though the same certification systems have been subjected to critique (Jaquet et al., 2010). Unfortunately, eco-labels do not normally consider energy use in the labeling scheme (Thrane et al., 2009), even if there are examples of labels have included this aspect, such as the Swedish KRAV label (krav.se).

Unfortunately, energy use of fisheries is one area of concern that still falls out of scope when setting management priorities (Tydmers et al., 2005). With present fisheries not only described by overexploitation of many commercially valuable fish stocks (Myers & Worm, 2003; FAO, 2010) and wasteful discards (Kelleher, 2005; Catchpole et al., 2005), but also as an industry heavily depending on fuel subsidies (Sumaila et al., 2008), more integrated approaches are needed for future fisheries development (Pauly et al., 2002).

Altogether, there is a societal need for the scientific community to search for robust and quantitative indicators for monitoring, communication and assessing or adjusting fishing policies to secure future fisheries in terms of food security (Cury & Christensen, 2005; Garcia & Rosenberg, 2010). Life cycle assessment (LCA) offers a transparent and integrated methodology to quantify all environmental impacts of relevance coupled to a certain product, with the aim to provide a broader perspective and identify hot spots and improvement potentials often from a cradle-to-grave perspective (ISO 2006a; 2006b). Environmental systems analysis methods, such as LCA, are further recommended to form the base for eco-labeling schemes (ISO 2006c). Could this tool for decision support be the panacea for fisheries management and the development towards an overall sustainable marine resource use?
4. Life Cycle Assessment and seafood production

4.1 General LCA methodology

Life cycle assessment (LCA) consists of four stages, however with an important iterative evaluation of the result from choices made in previous stages:

Goal & scope
Definition of the aim of the study, system boundaries such as which processes to include; the object of study (functional unit); choice of impacts to be studied; and other technical aspects such as allocation procedure, *i.e.* deciding on how to share environmental impacts in multiple outputs.

Inventory
The most time consuming part, where data on all resource use and emissions defined in goal and scope are collected and quantified in relation to the functional unit.

Impact assessment
All resource use and emissions inventoried are grouped into chosen impact categories and weighted together based on their relative impact contribution potential. For example, GHG emissions are weighted according to IPCC standards.

Interpretation of results
The sensitivity of the results from different inputs is, possibly resulting in changes of earlier choices made.

Defining the entity of focus, called the functional unit, is made in the goal and scope. This unit is studied in terms of resource use and environmental impacts, possible along the whole production and distribution line, life time and end of life, depending on the objective of the LCA. As many processes have a multiple output of products, various strategies for distributing the proportional environmental impact and resource use between the different products have been developed, called allocation. Preferably, according to the ISO standard this should if possible be avoided by increasing the level of detail (sub-dividing the system) or system expansion (using an alternative production system for one of the co-products). Otherwise this can be based on physical causal relationships between in and outputs based on e.g. the relative mass, energy or protein content of the co-products, or as the last alternative, based on other relationships (such as their relative economic value). In fisheries, this applies mainly to two situations: when several species are landed together and in processing of fish into various edible products as well as non-edible parts. There are different views on which allocation method is the most accurate for seafood production systems (see *e.g.* Ayer *et al.*, 2007; Pelletier *et al.*, 2011a), but it is important to remember that the choices made affect the absolute results and this complicates comparisons of results from different LCAs.
4.2 LCA of capture fisheries

In general, prior life cycle assessments of food products have concluded that the early life cycle stage, that is e.g. agriculture or fishing, has the dominating contribution in terms greenhouse gas emissions (GHG) and energy use per final product (Sonesson et al., 2010; Pelletier et al., 2011b). Vegetables are found in the lower range, whereas meat, especially beef, is found in the upper range. Seafood from capture fisheries exhibits broad values of GHG emissions, mainly attributed by fossil fuel use by the fishing vessel. The second important contribution to the GHG emissions from seafood production is possible leakage of refrigerants from cooling equipment on the vessels, if HCFC/HFCs are still in use (Winther et al., 2012). In agricultural based systems, other GHGs of non-fossil origin (biogenic) are more important, such as methane and nitrous oxides.

LCA’s of seafood production systems began in the early 2000s and have since then attracted increasing interest. As the method is young, methodological development is still needed (Pelletier et al., 2007), e.g. assessing impacts that are more complex to quantify, such as impacts on biodiversity (Curran et al., 2010). Due to lack of methods, focus has been on energy use and GHGs, and these assessments have brought some valuable identification of hot spots between different production systems (e.g. Winther et al., 2012; Vázquez-Rowe et al., 2010). There is however a risk of missing out in providing the comprehensive environmental perspective intended with the method by not having all necessary tools, for example assessing important components of a seafood product such as stock status, biodiversity effects and others with the same quantitative and integrated approach. It has been suggested that energy intensity could act as an indicator for other environmental impacts (Ziegler, 2006; Thrane, 2006), as there is a correlation between stock status and fishing method such as a depleted stock needs more fuel per kilo to land, due to e.g. lower landing per unit effort combined with longer distance to fishing ground (Hospido & Tyedmers, 2005).

A study confirming the energy need correlation to biological impacts is a LCA on Norway lobster (Nephrops norvegicus) caught with creel versus demersal trawl, were fisheries specific impacts new to the LCA framework were included (Ziegler & Valentinsson, 2008). Both swept seafloor area, discard amount and fuel use was found to be considerably higher for trawled Nephrops compared to creel caught ones. However, these findings were complemented with a study focusing on the Nephrops trawl fishery in the area, where the methodological framework for assessing impacts from discards was further expanded (paper I). Without differentiating impacts imposed from discards in terms of new approaches (such as quantifying the vulnerability of discarded fish species and the extra primary production required from discards), conventional trawling would come out as clearly superior to selective trawling as the greenhouse gas emissions are lower per kilo of landing. Even the total discard ratio was shown to be lower. However, by increasing the level of detail and distinguish between possible discard impacts, e.g. selective trawling have discards consisting mainly of less sensitive species (such as juvenile Nephrops) trade-offs in terms of discard impact and fuel efficiency can better be visualized.
4.3 Fuel use in Swedish Nephrops trawl fisheries

Fuel use, GHG emissions and biological impacts in former LCA’s on Nephrops are summarized in Table 1. Note that the figures are not directly comparable between the studies, as there are differences in goal and scope, importantly the choice of allocation method. Instead, it is attempted to illustrate how different methodological choices affect the absolute results in the studies.

Assessments of the Swedish Nephrops fishery has been done by Ziegler & Valentinsson (2008), Hornborg et al. (paper I) and Ziegler & Hornborg (in prep). The first study used fuel data from 19 questionnaires (of which seven were trawlers). The second study (paper I) applied a fuel model from a Danish study (Bastardie et al., 2010) on Swedish logbook data from 2009, accounting for differences in kW of the boats in the fishery. Based on interviews with fishermen, the model was adjusted to use 40% of kW. Transport assumptions were made regarding the length and speed of steaming to and from fishing ground, resulting in mean values for fuel consumption per landing based on all hauls during one year. The 40 % kW usage have later been found to possibly have been a bit optimistic, when the third study was made possible due to official release of aggregated data for 2009 in the Annual Economic Report on the European fishing fleet by the Joint Research Centre (JRC) of the European Commission (Anderson, J., et al., 2011; Ziegler & Hornborg, in prep). These results are sprung from a top-down approach, using data on the total fuel use by different fleet segments estimated from survey data collected by the Swedish Board of Fisheries. Allocating the total fuel consumption first by trawl hours (assuming that all demersal trawls have approximately the same fuel consumption within a size segment) and then by landing per hour from Swedish logbook data (effort and landings for different gears), an estimated fuel need per landing was obtained. From these results, it was found that approximately 80 % kW effect (if applied to all demersal trawl segments) would be more in line with the total fuel consumption for the fleets according to JRC. However, the lower results in (paper I) could also have been affected by the transportation scenarios chosen. It could also be that the estimates in the Annual Economic Report could be somewhat high. The fuel data in Sweden are unfortunately highly classified information, allowing raw data for independent research would have provided better starting point for all LCA studies on fuel use in fisheries, aiming to contribute important and integrated information to stakeholders, managers and the industry itself.

According to the Swedish Board of Fisheries, fuel use per kilo landing was in 2007 in the range of 2.5-3.8 l/kg for Nephrops trawling and 0.9-0.3 l/kg for mixed demersal trawling depending on boat size (Bengtsberg, 2007). However, the gear and boat definitions in this report was somewhat different than in Hornborg et al., (paper I), e.g. no separation between different selectivity of gears was made. In addition, both landings and fuel use differ between years, with possible effect on the fuel use per kilo seafood product (Ramos et al., 2011).
Table 1. Main LCA results from earlier studies including Nephrops fisheries. Important to note that the figures are not directly comparable as there are differences in goal and scope between the studies (with particular effects from using different allocation methods of attributing impacts per species in mixed fisheries). Discard$_{juv}$ refers to Nephrops.

<table>
<thead>
<tr>
<th>Gear</th>
<th>Year (data)</th>
<th>Country</th>
<th>Diesel (liters)</th>
<th>GHG (CO$_2$e)</th>
<th>Discard (kg)</th>
<th>Seafloor (m$^2$)</th>
<th>Discard$_{juv}$ (kg)</th>
<th>VEC (No.)</th>
<th>PPR$_{disc}$ (kg C)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed trawl</td>
<td>2004</td>
<td>Sweden</td>
<td>9</td>
<td>27.8</td>
<td>4.5</td>
<td>33 000</td>
<td></td>
<td></td>
<td></td>
<td>Ziegler &amp; Valentinsson (2008)</td>
</tr>
<tr>
<td>Mixed trawl</td>
<td>2004</td>
<td>Sweden</td>
<td>2.2</td>
<td>7.2</td>
<td>0.4</td>
<td>1.6</td>
<td></td>
<td></td>
<td></td>
<td>Ziegler &amp; Valentinsson (2008)</td>
</tr>
<tr>
<td>Mixed trawl</td>
<td>2009</td>
<td>Sweden (Kattegat)</td>
<td>1.8</td>
<td>5.5</td>
<td>1.7</td>
<td>15 000</td>
<td>0.8</td>
<td>2.7</td>
<td>89</td>
<td>Hornborg et al. (paper I)</td>
</tr>
<tr>
<td>Mixed trawl</td>
<td>2009</td>
<td>Sweden (Skagerrak)</td>
<td>1.3</td>
<td>3.8</td>
<td>1.2</td>
<td>10 000</td>
<td>0.2</td>
<td>3.2</td>
<td>120</td>
<td>Hornborg et al. (paper I)</td>
</tr>
<tr>
<td>Selective trawl</td>
<td>2009</td>
<td>Sweden (Kattegat)</td>
<td>2.4</td>
<td>6.8</td>
<td>2.5</td>
<td>22 000</td>
<td>0.8</td>
<td>1</td>
<td>88</td>
<td>Hornborg et al. (paper I)</td>
</tr>
<tr>
<td>Selective trawl</td>
<td>2009</td>
<td>Sweden (Skagerrak)</td>
<td>2.4</td>
<td>7.0</td>
<td>1.3</td>
<td>17 000</td>
<td>0.7</td>
<td>0.5</td>
<td>31</td>
<td>Hornborg et al. (paper I)</td>
</tr>
<tr>
<td>Selective trawl</td>
<td>2002-2009</td>
<td>Sweden</td>
<td>3.4-8.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ziegler &amp; Hornborg (in prep)</td>
</tr>
<tr>
<td>Mixed trawl</td>
<td>2002-2009</td>
<td>Sweden</td>
<td>0.5-1.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ziegler &amp; Hornborg (in prep)</td>
</tr>
</tbody>
</table>

1 Mass allocation
2 System expansion
3 Economic allocation
4 Mass allocation. The range illustrates different size classes of boats, with the lowest values attributed to the smallest boats (data from 2009).
5. Environmental impacts of capture fisheries

It must be noted that a range of scientific disciplines must be involved if to be conclusive on which categories of environmental impacts are of concern from marine capture fisheries and many with synergetic effects (Rogers et al., 2011; Noone et al., 2012). Many impacts are of concern to ecosystem functioning, which so far only have found to be highly complex and impossible to fully grasp in the marine environment (Stachowicz et al., 2007). Not surprisingly, whereas it has been repeatedly documented that fisheries in the longer perspective have impacts on biodiversity (e.g. McClenachan, 2009), the exact cause-effect chain leading to altered function and resilience, is not clearly established (Worm & Duffy, 2003; Duffy et al., 2007). Identifying which interactions that have the potential to affect the resilience of the ecosystem, not to mention quantifying the potential impacts, is unlikely to fully be possible to incorporate within a framework such as LCA or any other form of assessment at present level of understanding.

Identifying all biotic impacts important to consider in order to have a non-excluding approach of the LCA framework is therefore difficult, but a general rule of thumb could be target stock impacts, unintentional catches and seafloor disturbance. Within these three categories, there are several diversified impacts, as well as interactions within and between them. Further unwanted impacts from fisheries, besides these general issues are certainly of concern, such as interaction with seabirds (Cury et al., 2011). This thesis will not cover all areas of concern, but focus on indicators that could be used to assess different potential impacts from unintentional catches.

5.1 Target catch

The most obvious impact of marine capture fisheries at present would be removal of biomass that has led to stock depletion due to overexploitation (Jackson et al., 2001). Fish species formerly common on our dinner plates, and to some extent still are, have ended up on lists of species threatened with extinction (IUCN, 2011).

As a food production system, capture fisheries production depends to a greater extent on natural replenishment, i.e. ecosystem functioning, in comparison to most other types of food items, which rely on the intensified and more man controlled production systems of agriculture. This is important, as agricultural systems have brought on vast land transformations, with great effects on pristine diversity and ecosystem functioning (Foley et al., 2011); but while the agricultural landscape is now at times considered to be esthetically pleasing, even worth protection for cultural reasons, exploitation of the sea rarely does. In the marine environment, to keep everybody content, it would be desirable to have a pristine state at the same time as increasing the productivity of commercial species. Biodiversity effects of fishing are therefore considered troublesome from, at least, two points of view: they jeopardize the production capacity as well as cause a detrimental effect on the natural state of the marine ecosystem. As for production capacity, the question is on which level biodiversity is of importance to protect: species, stock, trophic level or community.
It could be argued that if the target stock is in a bad state, other impacts of concern such as unintentional catches are likely to be so too or not of relevance, and only focusing on stock status. However, this task is not easy and efforts are currently being made by Emanuelsson (in prep), as well as there are exceptions. The economically lucrative lobster fishery in Maine has boomed following depletion of local fish stocks (Steneck et al., 2011); the same situation could to some extent be applied to the Nephrops fishery on the west coast of Sweden. Simply being satisfied with the fact that the crustacean stocks are stable (ICES, 2011) does not necessarily imply that the fishery could be characterized as a sustainable resource use, as it has the potential to affect rebuilding of depleted fish stocks from possible high levels of unintentional catches of depleted fish stocks as well as it could have differences in seafloor area impact, some in no-trawl zones depending on gear use (paper I). Therefore, a range of complementing indicators is needed, in addition to target stock status, in order to assess fisheries sustainability and the environmental impacts.

5.2 Unintentional catches: By-catch and discards

By-catch is the part of the catch that is not directly targeted for. This part could be landed, i.e. brought to market, in general consisting of species with less information regarding stock status. Discard is the part of the by-catch that is directly thrown back to sea for various reasons, such as being of lower economic value, restricted by quota or being under the minimum size for being allowed to be landed. It has been estimated that the weighted average global discard rate in marine fisheries is 8 % (Kelleher, 2005), but this figure varies greatly in time, space and between fishing practices. Some fisheries in the North East Atlantic have the highest discard rates in the world, whereas artisanal fisheries by in general utilizing a greater proportion of the catch, have a lower amounts discarded (Kelleher, 2005; Ziegler et al., 2011). Prior studies have also identified that fishermen involvement and understanding are of great importance to reduce discards (Suuronen & Sardà, 2007; Catchpole et al., 2005b). Discard practices are presently of considerable concern for sustainable resource use, and efficient management to reduce discard is highly ranked on the political agenda in many parts of the world, e.g. in the upcoming reform of the Common Fisheries Policy of the EU.

5.2.1 Non-commercial species in discards

First, it should be noted that different categories of discarded species are subjected to different monitoring effort. Invertebrate taxa are generally insufficiently recorded and are hence excluded from this discussion, even though a study on sensitive non-commercial invertebrate composition in discards in the studied area for the case study (paper I), showed differences between fishing practices (Ottoson, 2008).

Marine mammals are unintentionally caught in global fisheries, the same occurs in some of the Swedish fisheries (Lunneryd et al., 2004). Globally, some mammals are being at risk of extinction because of high mortality from fisheries, such as the Vaquita porpoise (Avila-Forcada et al., 2012). Unintentional catches of mammals have however brought a lot of public attention, and has created incentives for special eco-labels, such as dolphin safe tuna (Thane et al., 2009).
Birds and turtles are also to a great extent being by-caught in fisheries (Žydelis et al., 2009; Wallace et al., 2010), with efforts made on technical solutions in order to avoid interactions. Marine mammals, turtles and birds would apply as “charismatic species”, and would most likely be included in the concept of Endangered, Threatened or Protected (ETP) in MSC assessments, with recommendations to avoid impacts on these case-to-case defined species for the fishery to be certified (MSC, 2011b). Fish and invertebrates in general attract less attention.

5.2.2 Discard of commercial species

Whereas the general importance to decrease discard has to some extent been hard to understand by fishermen (Catchpole et al., 2005ab), discarding fish of landing size (with no survival potential) due to quota restrictions has been more troublesome for fishermen. From a pure resource perspective, discard of juvenile fish is of great concern. It has previously been estimated that an end to discard of cod, haddock and whiting in the North Sea have the potential to increase the stocks with 41%, 14% and 29% respectively in ten years (Catchpole et al., 2007). In stock assessments of many commercial species, juvenile discard is now increasingly included in fishing mortality estimates.

Whereas discards of juvenile fish species is a substantially unwanted impact on fish resources and could impede stock rebuilding (Hutchings, 2000), discards of juvenile invertebrates such as Nephrops is more debated. The high discard ratios of juvenile Nephrops in the trawl fisheries in Sweden (paper I) originates from a high minimum landing size in the region. Castro et al. (2003) suggested that due to the higher survival potential for Nephrops than for many fish species, there is a net positive effect of releasing juvenile Nephrops instead of landing them all, i.e. a discard ban of juvenile Nephrops could prove to be negative for the stock. Having a high discard ratio of commercial invertebrates such as Nephrops, does therefore not necessarily imply that it is of great resource concern, especially if the discards are included in assessments as is the case with Nephrops in the studied area (ICES Advice 2010, Book 6).

For many commercial fish species mainly caught as by-catch, little or no direct management is in place. It has been estimated that approximately 40% of global landings comes from by-catches, if the definition would include all species lacking sufficient management (Davies et al., 2009). The sensitivity of these fish species to the operating fishing practices in the area would at times only be brought to attention when the decline is obvious and the species could be threatened with extinction (Brander, 1981). Therefore, it is of great importance to increase monitoring and different fisheries’ effect on these species, especially from the discarded part of the catch, which is rarely visualized.

5.3 Benthic impacts

Different gears have a varying seafloor contact, with demersal trawls, especially beam trawls, having the greatest impact and may cause severe habitat degradation (Watling & Norse, 1998; Hiddink et al., 2006). Seafloor disturbance is not a focus to this thesis, but needs to be mentioned as the area disturbed is quantified in relation to the seafood product in paper I.
the Kattegat area, intensive trawling occurs, affecting the same area often several times per year, leaving parts in a permanently altered condition (Nilsson & Ziegler, 2007). Quantifying the area disturbed should preferably take into account the vulnerability of disturbance caused by different gear constructions as well as the frequency of impact. The information found on the area of impact from a demersal gear is in addition surprisingly scarce.

Even if this area of concern is considered to be outside the scope of this thesis, it should still be noted, that the selective demersal trawls studied in paper I is allowed to trawl in no-trawl zones, possible causing different effect than trawling outside these zones, in addition to having a lower CPUE, i.e. more seafloor area affected per kilo of landing.

6. New approaches for by-catch assessments

6.1 Threatened species

Extinction risks for fish species has for long been thought to be less acute based on observations on a general higher fecundity, abundance and distribution range compared to threatened terrestrial animals (Reynolds et al., 2005). But the perception of an inexhaustible fish resource, reigning up until the great expansion of modernized fishing fleets, has had to be revised. The history of fishing is now known to have left several animal species extinct, or threatened with extinction, and fish stocks have been severely depleted, possibly with little recovery abilities (Jackson, 2001; Roberts, 2007). In e.g. the North Sea, it has been estimated that over 99% of the biomass of large fish species (16-66 kg) has been removed by fishing (Jennings & Blanchard, 2004).

The primary threats to fish species are over-exploitation and habitat loss (Roberts & Hawkins, 1999; Reynolds et al., 2005). By-catch management has especially been called for, with some long-lived, low fecund and large species complexes such as sharks and rays needing extra mitigation of the impacts imposed by the fishing industry (Hoffman et al., 2010). Related to seafood production, threatened species have so far mainly been considered as an ETP-concept within the MSC labeling scheme, where species listed by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) are in general the most considered (MSC, 2011b). As for fish species on the CITES list, only a few shark species and a handful of bony fish are listed, but with strong law enforcement restricting utilization.

On the other hand, the International Union for Conservation of Nature (IUCN) provides a red list of threatened species on a global, and for some countries, even on a national level (IUCN, 2011). The globally standardized assessment methods are generally based on abundance trends in relation to generation time. The IUCN approach has been shown to be of high consistency both in relation to life history parameters sensitive to fishing pressure (such as older age at maturity, larger maximum size and longer life span) and stock advice from the International Council for Exploration of the Seas (ICES) (Dulvy et al., 2005; paper II). Yet, the national red list of fish species has attracted minor attention to fisheries managers, even if in recent years fisheries has become increasingly restricted or even closed for some of the
species listed, such as European eel (*Anguilla anguilla*) and spurdog (*Squalus acanthias*), but not all as in the case with *e.g.* whiting (*Merlangius merlangus*) (Swedish Board of Fisheries, 2011). The World Wildlife Fund (WWF) in Sweden suggests the consumers to avoid all species occurring on the red list in their seafood guides, unless a stock is certified with an eco-label (*e.g.* Eastern Baltic cod, KRAV-certified).

The aim with the red list is to provide an alarm signal when a decline of a species is not originating from a regulated exploitation (Mace & Hudson, 1999). This makes the approach ideal for protecting species lacking management, as would be the case for unintentional catches in fisheries. In paper II, it was found that fish species with greater values for age of maturity, life span and maximum length were progressively found in categories of higher threat status, which could make the red list status a carrier for aggregated information on fishing vulnerability. By studying differences in amounts of red listed fish species in discards (VEC; Vulnerable, Endangered or Critically Endangered according the national IUCN red list) between demersal trawling segments in the Kattegat and Skagerrak area, it was found that for every ten kilos of *Nephrops* landed by conventional trawl, 30 red listed fish were discarded, whereas the equivalent for ten kilos of Northern shrimp (*Pandalus borealis*) landed with a species-selective trawl, only discarded one red listed fish (paper I). Differentiating sensitivity of impacts from unintentional catches attributed to a seafood product by estimating the mass or individuals of threatened species discarded per landing could serve as an appealing indicator to quantify impacts on sensitive fish species.

Discussions are ongoing on whether protecting dominating species or key stone species, *i.e.* species with great importance to ecosystem structure, are of greater importance to protect than rare species (Jordán, 2009). However, as the demersal fish biomass in the North Sea is dominated by a few species (*e.g.* cod, whiting and haddock) (Jennings et al., 2002), finding them all now on a list of threatened species is of great concern from both viewpoints. If formerly dominant species now are rare in relation to historic levels (as is indicated by the VEC approach), the impact potential in terms of ecosystem effects could be seen as alarming, both from a key stone species/dominant/rare species perspective.

### 6.2 Food web interactions

Species are assigned to different trophic levels (TL) in the food web, with primary producers having TL=1 and being the most abundant in terms of production, their consumers TL=2, with less mass than for the lower trophic level and so on shaping a pyramidal structure with increasingly less biomass being able to be sustained due to limitations from energetic transfer dynamics. The TL of a species varies *e.g.* during the species life cycle and season and is therefore not a constant (Jennings et al., 2002), these estimates are coupled with great uncertainties. Estimates of the TL of fish species are at present made from fractional diet composition (found at fishbase.org) or by stable nitrogen isotopes (*e.g.* Pinnegar et al., 2002). A comparison between the two methods indicated some differences, such as higher trophic levels could be derived by stable nitrogen isotope studies, which are believed to originate from the complexity of predation patterns of soft bottom- and plankton communities.
This thesis’ focus on trophic distortions is mainly related to how to quantify and differentiate impacts between different fishing practices on trophic energetics, in particular commercial and non-commercial fish and commercial invertebrates in discards. It should be noted that ecosystem dynamics are complex and involve several other species such as marine mammals, reptiles, etc., where fisheries e.g. could cause trophic implications by competing for food or altering competition within the bird complex (Tasker et al., 2000; Cury et al., 2011). However, the attempt made here is to discuss the implications from fisheries with different discard compositions, and how trophic indicators could be interpreted within the LCA framework.

From a pure resource perspective, i.e. effects on the ecosystem’s potential fish production, it has been suggested that the fish production depend on various factors such as e.g. the number of feeding links (Lindeman, 1942), efficiency of energy transfer (Ryther, 1969; Iverson, 1990), consumer body size (Denney et al., 2002), nutrient availability (Chassot et al., 2007) and species richness (Frank et al., 2007). Top predators have often been exploited at unsustainable levels, causing trophic distortions. As these species in general are slow growing with low reproduction rate, this has led to the depletion of many predatory fish stocks (Christensen et al., 2003; Myers & Worm, 2003), which make this impact a concern even from a threatened species perspective (paper II). The trophic implications of the depletion of top predators in terms of ecosystem functioning are not clear, but uneven targeting patterns on top predators have been shown to cause regime shifts (Casini et al., 2009). Different geographical regions have however been found to have varied energy dynamics, with evidence for top down (predator) control as well as established bottom-up (primary producer) controlled trophic linkages (Frank et al., 2005; Ware et al., 2005). Energy transfer control can also be dependent on a few species at intermediate trophic level controlling the energy transfer between upper and lower levels, called “wasp-waist”-ecosystems (Cury et al., 2000). It has been suggested that due to the sequential depletion of top predators, fisheries are forced to increasingly turn to species at lower trophic levels, known as “fishing down the food web” after it was shown in global landing statistics as a decreased mean trophic level of landings (MTL; Pauly et al., 1998).

Mean trophic level (MTL) of fisheries landings is at present an operational indicator for the Convention of Biological Diversity (CBD) as “Mean trophic index” (MTI) and is stated as an indicator ‘ready for global use’ (CBD, 2010). The findings by Pauly et al. (1998) have since then however been heavily debated in terms of what could possibly be interpreted from using landing data, which is affected by changes in management such as quotas and gear usage (Branch et al., 2010), and somewhat revised, with new concepts such as e.g. “fishing trough marine food webs” (Essington et al., 2006) and a “fishing in balance”-index (Pauly et al., 2000). In Hornborg et al. (paper III), the management effect on MTL is further reinforced by studying MTL in official landing statistics, survey data and total catch (including the discarded part) in separate demersal trawling segments in the same area (Kattegat and Skagerrak). The results showed that it is evident that e.g. turning to species selective trawling for invertebrates would result in a lowered MTL of landings, which is unwanted from the CBD perspective. The same effect on MTL would arise from conventional trawling for e.g.
Nephrops when quota restrictions on depleted fish stocks are enforced. The great difference in terms of possible ecosystem effect would be in the MTL of the total catch (or the discarded part), further reinforcing the necessity to use catch data instead of landing data when evaluating the MTL indicator trend globally (sensu Branch et al., 2010).

Closely related to MTL is the concept of Primary Production Required (PPR) from fisheries landings. PPR is an estimate of the amount of carbon that has been needed to produce one kilo of wet weight of a species at a certain trophic level (Pauly & Christensen, 1995). PPR is estimated from assuming a 9:1 ratio for conversion of wet weight to carbon (Strathmann, 1967) and using estimates of transfer efficiency (TE), i.e. the proportion of production that is retained in transfers between each trophic level (TL) (Lindeman, 1942). TE varies between e.g. ecosystems, but has been suggested to have a global mean of 10% (Pauly & Christensen, 1995). The PPR estimate thus assumes that fish production is limited by carbon transfer, that it is a constant transfer along the food chain and independent of the length of the food chain. It must be acknowledged that all of these assumptions could be discussed (Baumann, 1995).

Due to the great uncertainties surrounding estimates of TE and TL, comparative studies on PPR from fisheries from different regions using either differentiated TE or the global average of 10% is dubious. Short transfer chains (e.g. in upwelling areas) have relatively robust PPR estimates, as fewer links are involved (and hence the sensitivity to differences in TE values), as well as the fish species occurring in general have a lower trophic level (which have lower TL uncertainty). On the other hand, longer transfer chains (e.g. temperate shelves areas), are much more sensitive to even the smallest uncertainty in trophic level or trophic efficiency, resulting in greater uncertainties to the PPR estimate (Baumann, 1995).

The PPR concept implies that exploiting species with different TL differs in terms of ecosystem cost (Pauly & Christensen, 1995), where the currency is PPR, and a higher value per landing is a greater disturbance to the ecosystem than a lower (ICES, 2005). It must be noted that there are regional differences between possible impacts (Frank et al., 2007), where e.g. the highly nutrient rich Baltic Sea would be at one side of the scale, and the oceanic systems on the other (Conti & Scardi, 2010). In addition to this, exploiting fish species at lower trophic levels (with a lower PPR) could also only be considered to be sustainable up to a certain limit in terms of absolute quantities, without causing effects on the upper trophic levels (Smith et al., 2011).

The percent of available primary production required from fisheries varies between regions, with the heavily exploited continental shelves having a value between 25-35% (Pauly & Christensen, 1995). This level of appropriation is high, as it has been suggested that only 41% of the coastal phytoplankton is at all consumed and moved up through the food web (Duarte & Cebrian, 1996). Upwelling areas show the highest %PPR from fisheries, with lower probabilities of sustainable exploitation at current exploitation rate (Coll et al., 2008; Chassot et al., 2010). The highest and long term sustainable fishing yields have been shown to occur from a combination of moderate fishing pressure and catches having a low to moderate MTL (Conti & Scardi, 2010).
Evaluating Swedish fisheries landings on the west coast during the last century with the trophic indicators MTL and PPR identified constraints to present use, as well as what could possibly be interpreted from the indicators (paper III). According to these findings, MTL is better used to evaluate the relative trophic impact from a fishing gear or targeting behavior within the same region. Demersal trawling could have between 5 - 80 % of the PPR from the landed part depending on gear and targeting behavior. If the fishery is mainly performed by selective trawling for invertebrates or by mixed trawling, MTL and PPR per landing will be affected differently. Selective trawling for invertebrates would decrease PPR per landing, in line with the requirements for a more sustainable resource use (Coll et al., 2008; Chassot et al., 2010; Swartz et al., 2010); on the other hand, MTL of landings would simultaneously decrease, which is an undesired outcome to the CBD.

Increased routine assessments of PPR of discard are valuable for better estimates of the true level of resource use. Coll et al. (2008), in lack of true values, added different theoretic levels of PPR from discard when evaluating the long term sustainable yield of fisheries per Large Marine Ecosystem (LME). The probability of being sustainably fished was increasingly lowered with higher discard PPR assumed, indicating the importance of including this part of resource use as well. In line with this, it has also been suggested that PPR standardization enables marine footprints to be compared between different fisheries (Swartz et al., 2010). For this to be operational, it is necessary to use catch data instead of landing data. In environmental systems analysis of seafood production, discard PPR could be compared with feed appropriation of primary production in aquaculture, assessed before as Biotic Resource Use (Papatriphon et al., 2004). The PPR approach for discards clearly show that discards are a hidden cost of fisheries: discard PPR from capture fisheries can be in the same range as the appropriation of feed production used in salmon culture per kilo of live weight salmon (paper I; Pelletier et al., 2009). It is however important to combine the PPR value with information on sensitive species affected, such as the VEC-approach (paper II). Little can otherwise be said when comparing different values of PPR from discards (as is done in Vázquez-Rowe et al., 2012).

For PPR to be considered as an impact of resource limitation, the value must be placed in a historic context (paper III). Even if it has been suggested that European seas are controlled by bottom-up processes (Chassot et al., 2007), it must be noted that the primary production in the studied area (Kattegat-Skagerrak) increased due to eutrophication from levels around 100 g C/m2 in the 1950s to 200 g C/m2 in the 1990s (Richardson & Heilmann, 1995). This increase has even been suggested to cause increased yields in pelagic fisheries in the Kattegat in the 1950s-1970s (Nielsen & Richardsson, 1996). However, with time, total landings have decreased in the area. The ecosystem at present leave primary production “underutilized”, with detrimental effects on coastal habitats such as hypoxia (Pihl, 1994), possibly a combination of eutrophication and fisheries ecosystem effect on functional biodiversity from uneven targeting patterns.

Last but not least, it should be noted that using theoretic TL, MTL and PPR values, little can be said on true ecosystem implications of Swedish fisheries during the last century. Herring is, and has been, dominating in terms of quantity in Swedish landings (paper III). This is one
of the few species that has been found to not have a strong positive relationship between increasing size and trophic level - as well as it has shown to have a decrease size spectrum as fisheries exploitation progress (Jennings et al., 2002). This implies that the bulk of Swedish fisheries landings (i.e. herring) could in fact have increased in trophic level with fishing exploitation. In the Baltic, another amplifying effect of TL change is the introduction of the invasive fish-hook water flea (Cercopagis pengoi), where changes in the zooplankton community increased the trophic level of herring in the Baltic from 2.6 to 3.4 (Gorokhova et al., 2005). Both these facts illustrate important divergence between trophic level estimates and the not accounted variability found in the ecosystem, with great implications to historical patterns of MTL and PPR in fisheries.

To conclude, by promoting different gears and setting quotas for species based on the total catch PPR value instead of merely landings, a step towards Ecosystem Based Fisheries Management (EBFM) is made. However, as the PPR does not say anything of the status of the species in the ecosystem (i.e. if species discarded are overexploited or of no concern), makes it important to complement PPR with information on the sensitivity (such as VEC; paper II).

7. Fisheries management and LCA

The major contribution so far from environmental systems analysis of seafood production is the coupling of abiotic resource use and impacts, such as fossil fuel need and greenhouse gas emissions to a seafood product. It has been estimated before that a global average of 0.62 liters of fossil fuel is burnt per kilo landings (Tyedmers et al., 2005). However, as global landings are dominated in mass by pelagic fisheries (FAO, 2010), highly energy efficient per kilo of landing (Thrane, 2006, Tyedmers et al., 2005), other fishing methods, such as demersal trawls, have been found to have considerably higher fuel requirements per kilo of landings (Ziegler & Valentinsson, 2008). Energy use per kilo of flatfish can e.g. be 15 times higher using a beam trawl compared to Danish seine (Thrane, 2006). Due to differences in energy consumption between capture methods, in combination with the findings that the fishing phase is the most important contributor to the energy needed during the life cycle of a seafood product (Ziegler et al., 2003; Thrane, 2006; Ziegler & Valentinsson, 2008; Magerholm Fet et al., 2010), management of the fishery is of great importance for the outcome of the environmental impact from a seafood product from capture fisheries (Winther et al. 2012). Decisions on e.g. gear use (Vázquez-Rowe et al., 2010; paper I) have a potential to strongly affect the total outcome of seafood LCA’s.

The broadened perspective that a LCA evaluation brings is also of cumulative importance to fisheries management, from both an environmental as well as an economic perspective as the fleet is highly depending on fossil fuel that is becoming increasingly scarce and expensive. Several environmental impacts attributed to a seafood product can be seen as a failure of management. Overexploitation (decisions on quotas, fleet size, effort and lack of observance) leads to a lower landing per unit effort (LPUE). Lower LPUE results in longer fishing time to land the same amount, with increased total fuel consumption, possible greater seafloor disturbance and increased discards when compared within the same fishery. As fuel use in fisheries has not so far been a concern to fisheries management, but instead has been
encouraged by vast subsidies, this neglect is resulting in a net income loss from fishing to society (Arnason et al., 2008) as well as an increasing energy need per kilo of seafood product (Tyedmers, 2004; Schau et al., 2009), preventing necessary structural adjustment in the fleet.

Two previous LCA studies have quantified the direct implications of fisheries management decisions on energy use and accompanied GHG emissions. The first was a case study on the New England Atlantic herring fishery (Driscoll & Tyedmers, 2010). By looking at the effect of altered management regulations on gear and quota allowances, the study identified a range between 21-116 liters of diesel per ton of landed herring; with a totaling range between 945 000-5 220 000 liters to fill the quota. Discard differences between gears were stated in the study, but there was no further elaboration on the biological implications in relation to the fuel need. In the second study, biological impacts (such as differentiated discard impact and seafloor area affected) was quantified in parallel with energy need of the Nephrops caught in the demersal trawl fishery on the Swedish west coast (paper I). In this study, a trade-off between local (the protection of local stocks) and global effects (increased GHG emissions and fuel use) of management decisions regarding the promotion of a species selective trawl to protect local cod stocks was visualized.

The result from the two case studies clearly shows that even if rebuilding of stocks is possible and underway (Worm et al., 2009), it is important to quantify seafloor impact, fuel use and discards coupled to harvest of the decided TAC, effort and gear regulations. Fuel use and other biological impacts from fisheries do not necessarily go hand in hand, and even act in opposite directions during stock rebuilding if selective demersal trawling is promoted in order to protect collapsed fish stocks (paper I). Acknowledging potential trade-offs outside present management consideration is a necessity when aiming for an ecosystem based management and an overall improved resource use.

This concern is of increasing importance with respect to present movement towards selective gears in order to e.g. minimize interactions between fisheries targeting stocks in good condition and rebuilding depleted stocks (Hall, 1996; Catchpole et al., 2005b). Within the European Union, a discard ban currently under discussion within the reform of the EU Common Fisheries Policy (CEC, 2009) is boosting the process by suggesting more selective practices. Some passive gears, such as creels, targeting the same species, have been shown to have lower fuel intensity relative to active gears as well as with less seafloor impact and lower discard rate with higher survival upon release (Ziegler & Valentinson, 2008). Promoting selective demersal trawls, that are likewise energy intensive and destructive in terms of seafloor disturbance as other demersal trawls (but have a lower catch per unit effort), are however more challenging in a broader context to be used to protect stocks (paper I). Which environmental trade-offs are acceptable for protecting depleted local fish stocks? From an LCA perspective, it would be superior to promote the best available technology (in this case creeling) and to cut the trawling fleet, instead of making it less effective. This could also prove to be favorable from a socioeconomic perspective, as increased fuel costs in combination with decreased landings from overcapacity have been and are troublesome to the general profitability of the Swedish fishery (Bengtsberg, 2007).
When studying the fuel intensity in the whole Swedish demersal trawl and seine fishery in the last decade, a trend of decreasing fuel use is however now seen (Andersen & Guillén, 2010). The landing per unit effort has in general increased, but with a constant fuel use per effort, the decreased effort result in increased fuel efficiency (Ziegler & Hornborg, in prep.) It would have been interesting to know what an even stronger capacity cut would have done for the total fuel consumption in Sweden in relation to the movement towards energy intensive gears with lower LPUE such as selective trawls. Of the total mass of landings by demersal trawls and seines in Sweden, Nephrops only represents around 5 %, which means that the overall result of the species-selective trawling having higher fuel consumption per kilo of landing is undetectable in statistics when aggregated in national fleet segments (demersal trawling is dominated by Baltic cod trawling). With this argument, the increase of fuel need per kilo of Nephrops by selective trawling could be considered a small problem, given its minor contribution to the total fuel consumption of the fleet.

Finally, a small economic note should be made. As there has been a minor increase in proportion of Nephrops in demersal landings in mass in comparison to the relative value of the species in the catch (figure 2), and as at the value of Nephrops have been relatively stable during the time period (at approximately 9-10 Euro/kg), the decreased fish landings in the trawl fishery has increased the economic dependence on Nephrops. Due to the relatively high price of Nephrops landings, turning to selective trawling for Nephrops in Sweden has been successfully implemented, even if it can be considered to be forced from effort restrictions on trawling catching cod (paper I).

A study on the profitability of selective trawling for Nephrops showed that in terms of short-term profitability, selective trawling could be troublesome but more profitable in the long term (Macher et al., 2008). However, it should be noted that the development of a fishery towards highly priced single species due to depletion of other stocks is sensitive, both from an ecological and socio-economic perspective (Steneck et al., 2010). It might be proposed that instead of turning to selective trawling practices (due to depletion of fish stocks), new approaches, such as other gears deployed and greater areas protected from fishing to rebuild fish stocks, should be enforced until overcapacity is resolved. Most recently, general concerns

Figure 2. Percentage of total value and mass respectively attributed to the Nephrops part in demersal trawls in Sweden (Andersen & Guillén 2010).
have also been expressed on the ecosystem effects of selective fishing, propagating for utilizing a mixed size and species catch (Garcia et al., 2012).

9. Conclusions and future outlook

This thesis combines the abiotic assessment framework of LCA with the biotic impacts of fisheries and fisheries management and contributes to increased assessment of unintentional catches within the LCA framework.

It was found that two complementing discard indicators are needed. PPR in discards does not reveal anything on impact of sensitive species (VEC), which therefore is an important complement. As for applying VEC globally in seafood LCA’s, IUCN assessments must increase their coverage of marine fish species. The PPR approach must also be made with caution, as the values must be placed in the right context (such as nutrient availability) and which transfer efficiencies values that should be used when comparing seafood products from different regions. By adding information on discard quantity of threatened fish species (VEC) in combination with the primary production required (PPR) to produce the discard, environmental assessments of seafood production can move towards a more integrated approach, at least in terms of impacts from unintentional catches.

By using a life cycle approach, broader evaluations of fisheries management can be made, visualizing not considered potential trade-offs in an integrated format. This is of increasing importance to fisheries managers to achieve an overall sustainable resource use in world fisheries. It is time to shift gear and turn to the best practice in the longer and broader perspective. Instead of quick fixes, such as promoting selective demersal trawls to mitigate wasteful discards, changes to reigning policies in line with the discussions in Garcia et al. (2012), or promote other types of gear that are not questionable in a broader perspective, must be made.

Planned future work will be focused on size selectivity. The selectivity of the gear is not only the main reason behind different quantities of unintentional catches, but also different size exploitation of the targeted species. As fishing normally target larger individuals in an exploited stock, due to high value and restriction on minimum landing size, there is an increasing concern for “fisheries induced evolution”. This concept implies that the targeting of the largest individuals put evolutionary selection pressure on certain individuals, resulting in progressively smaller individuals/mean size and lower yields of the exploited species (Conover & Munch, 2002; Kuparinen & Merilä, 2007). A size related indicator of fishing impact is therefore of high relevance (Jennings et al., 2002), and could in theory combine the VEC and PPR approaches for both target and by-caught fish stocks. Species of high trophic level most often have a high $L_{\text{max}}$ and are more often found on the IUCN’s red list of threatened species. Larger species are also most often top predators. By shifting focus to cod stock management in the coastal areas of Sweden, including the Baltic Sea, this issue is to be further explored.
References:


FAO (2010). State of the World’s Fisheries and Aquaculture. FAO Fisheries and Aquaculture Department, Food and Agriculture Organization of the United Nations, Rome


ICES (2011) Stock advice for Nephrops in ICES area IIIa are available at http://www.ices.dk/advice/icesadvice.asp


ISO (2006c) Environmental labels and declarations - Type III environmental declarations - Principles and procedures ISO 14025:2006


Ziegler, F. & Hornborg, S. *In prep*. The energy use of Swedish demersal fisheries between 2002-2009 in relation to management, stock status, fuel price and technology. Work originally commissioned by the OECD’s Fisheries Policies Division
