DELIVERABLE FRONTPAGE

Project number:	243827 FP7-ENV-2009-1
Project acronym:	LC-IMPACT
Project title:	Development and application of environmental Life Cycle Impact assessment methods for improved sustainability characterisation of technologies.
Deliverable number:	D 4.7
Deliverable name:	LCA case study – fisheries
Version:	1
WP number:	4
Lead beneficiary:	SIK
Nature:	R[1]
Dissemination level:	PP[2]
Delivery date Annex I:	M40 (month number)
Actual delivery date:	27/04/2013
Authors:	Andreas Emanuelsson, Friederike Ziegler, Sara Hornborg, Ulf Sonesson
Comment:	**Several parts of this deliverable will be published in scientific journals and need to be treated confidentially until the publishing date (for internal EU review only).**

---

[1] Please indicate the nature of the deliverable using one of the following codes: **R** = Report, **P** = Prototype, **D** = Demonstrator, **O** = Other

Photo credits: The Swedish Cod Fishermen’s’ Producer Organization (STPO), an association of fishermen primarily fishing cod from the Baltic Sea. The producer organization is open to trawlers, gill-netters and long-liners.

D4.7 LCA case study fisheries:

Benchmarking Swedish cod and herring products by spatial-temporal Life Cycle Assessment

Andreas Emanuelsson[1], Friederike Ziegler[1], Sara Hornborg[1], Ulf Sonesson[1]

[1] SIK, The Swedish Institute for Food and Biotechnology, Göteborg, Sweden.

Summary

The case study ***"Benchmarking Swedish cod and herring products by spatial-temporal Life Cycle Assessment"*** *demonstrates a state of the art application of seafood LCA incorporating new methods to cover target stock and ecosystem sustainability, in an environmental midpoint benchmarking of the Swedish trawl fleet in the Baltic Sea. This was done by comparing average products originating from fishing activities on two fish stocks of cod and two fish stocks of herring in 2008 (spatial resolution). In addition, one stock of each species was compared over time in terms of key drivers, i.e. between 2002 and 2008 (temporal resolution).*

Newly developed/refined impacts categories of Lost Potential Yield (including supporting impact categories of Overfishing through Fishing mortality and Overfishing of Biomass, Primary Production Required and revised Swept Area methodologies were applied together with a full set of ReCiPe midpoint impact categories. Also Threatened fish species in discards (VEC) was considered qualitatively but left out of the quantitative study and coved only by total discards (TD), due to lack of inventory resolution. Also a discussed possible final endpoint assessment including the new abiotic and biotic impact categories was left out as the actual methodologies would have had incomparable impact indicators, although both measured in economic units. The new impact categories used are in this report evaluated in terms of a) availability of inventory data required b) reflections about the application and c) interpretation of the results.

Case study results reveal a more complex picture of the four fisheries, emphasizing the stock, not the species as an important unit of comparison. Western Baltic cod generally performed worst in all categories, and Bothnian "Northern" herring performed best. However, Eastern cod and herring are harder to rank as they perform differently in the different categories included. One of the conclusions is that fishery specific impact categories aiming to describe direct physical damage to the natural ecosystem and the biotic resources retrieved from marine ecosystems requires some novel approaches for application, as they typically focus on a larger set of indicators describing parameters at mid-point level which all put different challenges for an LCA practitioner. Some of them could be dealt with by harmonization, guidelines and further method development, while others may challenge tradition nomenclature if applicability and biological relevance shall be prioritized. A final conclusion is that the inclusion of target stock and ecosystem aspects should be a default check for future seafood LCAs, preferably included quantitatively, otherwise qualitatively or clearly stated in the goal and scope if such a relevant flow is left out and that the LCA does not reflect the full environmental performance.

Table of Contents

1. Introduction

Sustainable fish products has gained growing interest among consumers and other seafood supply chains stakeholders, which has led to rapid increase in the number of certified fisheries (Stokstad 2011). However existing labels are seldom quantitative and specific about the included aspects, nor emphasizing a holistic view of the production system from cradle to grave, including biological impacts as well as post-landing emissions and raw material demand (Thrane et al. 2009). Benchmarking of performance indices, including environmental performance, i.e. relating quantitative indices to reference situations, has become common tool for businesses to relate to others businesses, which ultimately aims at identifying and adapting better practices (Stapenhurst 2012).

Life Cycle Assessment methodology has been concluded by the European Commission to provide the best available framework for assessing the potential environmental impacts of products (EC 2003). Yet until now, no LCA case study has quantified the direct impact on the targeted stocks as formal impact category when assessing seafood products. To do this, we choose a study of the Swedish trawling fisheries in Baltic Sea, as it provides known reference situations and a relevant scenario for evaluating the usefulness of environmental benchmarking on a national stock level, since it is the highest resolution in relation to exploitation advice and national regulations. Thus, we used environmental benchmarking of average products originating from stocks to evaluate the usefulness for different stakeholders and relate the highest potential environmental impacts to prioritize improvements or decision support for various stakeholders.

This report is structured in nine sections, after this introduction follows chapter 2, a background description including state of the art impact assessment and case study specific information about the Swedish fisheries in the Baltic Sea. Thereafter follows and chapter 3, a Goal & Scope ("material and method") section 3, but since the focus of this work has been on the novel impact assessment and its application, this is covered more thoroughly in a following separate chapter 4. Here we explain the new methods used ***(see also the complementing WP1 report)*** *and assess the usefulness and application consideration necessary. The complete relative and absolute results from the case study in itself are found in chapter 5 followed by discussion of the main results, conclusions, acknowledgements, references and supplementary information.*

2. Background

2.1. Impacts of fisheries

Overfishing of target stocks may seem like the most obvious aspect to include in an environmental benchmarking of fisheries, given that over 80% of the worlds fish stocks are considered fully exploited or overexploited by the United Nations Food and Agriculture Organization (FAO 2012).

As fisheries exert uneven fishing pressure on different components of the ecosystem, the entire ecosystem is susceptible to trophic cascade effects (Frank et al. 2005). Coastal and offshore fishing pressure has been shown to induce regime shifts, from which a restoration to previous state is unlikely, even if the fishing pressure is decreased (Jackson et al. 2001; Möllman et al. 2011).

In economic terms, global fishery systems are sub-optimized, leaving many fisheries with low profitability due to low stock sizes and overcapacity, but if the stocks were allowed to be restored to the full reproductive capacity, the global profits has been estimated to increase with five billion USD annually (FAO 2008). Only in Europe this has been approximated to equivalent 100 000 new jobs (Crilly and Esteban 2012). This follows the concept of Maximum Sustainable Yield (MSY), which has been reinstated as a management goal for the European Union (EC 2006).

Discards of unwanted catch is another global problem, as in total 8 % of the total catch is returned dead or dying back to the sea (FAO 2005). Single fisheries can have much higher discard rates, such as beam trawling in the North Sea with 71-91% of the catch being discarded (Catchpole et al. 2005).

Mechanical disturbance of seafloor ecosystems by mobile fishing gear has also been shown to have the potential of altering habitats (Hiddink et al. 2006; Pauly et al. 2002). Different habitats exhibit different sensitivity to trawl impacts (NRC 2002) and one assessment suggests that the total swept area by trawls each year corresponds to 40% of all shelf area available globally (Kura et al. 2000).

Besides the biological impacts, the global fishing fleet has also been estimated to use around one per cent of global oil production (Tyedmers et al. 2005) causing greenhouse gas emissions (GHG) to a large extent determined by the combustion and production of fuel used on the fishing vessels (Pelletier et al. 2007), but also the leakage of refrigerants from cooling systems (Ziegler et al. 2012).

Indirectly, GHG emissions affect marine ecosystems both with raised temperature and from ocean acidification by an increase in dissolved of CO_2 (Doney et al. 2009). The extraction and combustion of fuel also leads to range of other airborne emissions such as sulphure dioxide (SO_2), nitrogen oxides (NO_x) and volatile organic compounds (VOCs) contributing to various environmental impacts like acidification, eutrophication and ground level ozone formation.

2.2. State of the art

The theory behind biotic resource use in LCA was pioneered by three methods in the 1990ies, that after reviewed by the Society of Environmental Toxicology and Chemistry (SETAC) led to the conclusions of two folded impact pathways separating resource and ecosystem damage It also include a forecast, and in the future more sub-impact categories will be formed to tackle the heterogeneity of impact pathways, under the broad impact category ”biotic resource use” (Haes et al. 2002). Today over one hundred seafood production cases have been described with LCA since the 1990ies including both fisheries and aquaculture systems, which often requires wild caught feed inputs (Parker 2012). A rapid increase of Seafood LCAs have been recorded, which in 2011 represented one third of all published food LCAs (Avadí and Fréon 2013), but none of the original methods (Haes et al. 2002) have been used in the published seafood LCA case studies (Pelletier et al. 2007; Parker 2012; Vázquez-Rowe et al. 2012a; Avadí and Fréon 2013), possibly due to lack of applicability.

The missing of target stock methodology has limited the scope in seafood LCA's which has been concluded to “significantly impair the value for LCA as a management tool” (Pelletier et al. 2007). Yet a wide range of seafood specific impact categories approaches have been pioneered, but mainly regarding bycatches and discard (Ziegler et al. 2003; Emanuelsson 2008; Ziegler et al. 2011; Vázquez-Rowe et al. 2012b), and recently also characterized based on primary production requirements and frequency of occurring red listed species (Hornborg et al. 2012). Some methodology for seafloor disturbance area (Ziegler et al. 2003) and specific aquaculture methods (Ford et al. 2012) has also been presented, but a simple and straightforward guideline on how to include target stock overfishing is thus still absent.

2.3. Swedish fisheries in the Baltic Sea

Atlantic herring *Clupea harengus* L. and Atlantic cod *Gadus morhua* L. are today the two most economically important fish species landed in Sweden (JRC 2010), and the Baltic sea fishing area provided with 70% of the national landings 2008 (SNBF 2010). Within the Baltic Sea there are several subpopulations (or stocks) of cod and herring, which are assessed separately by the International Council for the Exploration of the Seas (ICES). Baltic cod fisheries are based on two stocks – a smaller “Western cod” stock (in subdivision 22-24) which represented 22% of Swedish cod landings in 2008 and a larger “Eastern cod” stock (in subdivision 25-32) which represented 72% of Swedish cod landings in 2008 (figure 1a). The two stocks are separated genetically and geographically (ICES 2011). Four different herring stocks are managed separately in the Baltic Sea, but only the two largest stocks are included in this study; “Eastern herring” (subdivision 25-29 and 32 excluding gulf of Riga) which in 2008 represented 81% of the Swedish herring landings and the “Northern herring” (in subdivision 30, i.e. Bothnian Sea) representing 5% of Swedish herring landings.

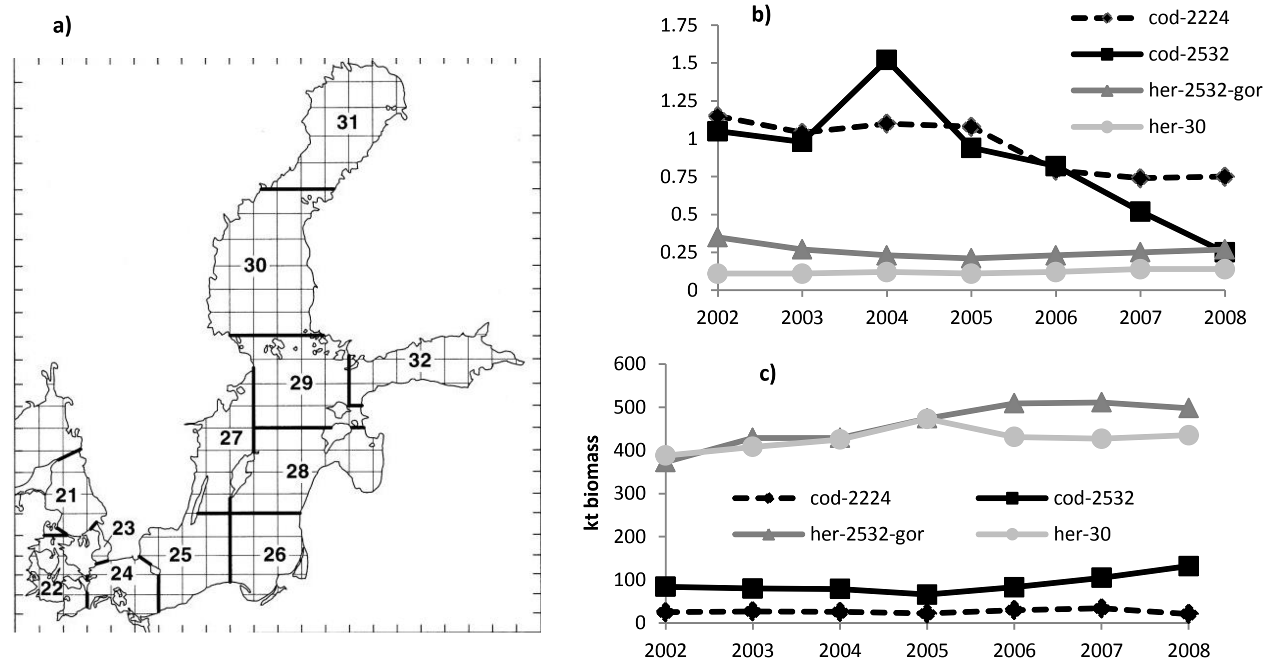


Figure 1. a) ICES subdivisions of the Baltic Sea, b) Fishing morality (F) c) Spawning stock biomass (SSB) of four stocks of cod and herring 2002-2008. Western cod =cod-2224; Eastern cod=cod-2532; Eastern Herring=her-2532-gor; Bothnian sea herring = her-30.

Swedish herring landings in the Baltic have been roughly constant during the last decade, while cod landings decreased with 23% during the same period. The fishing mortality of both cod stocks was initially very high in 2002, where the annual landings exceeded the estimated size of the spawning stock (table 1). ICES recommended large quota reductions, which were only partly implemented. However, the fishing pressure of eastern cod decreased drastically until reaching a level actually lower than the F_{MSY} in 2008, the fishing mortality that over time would lead to long-term sustainable catches (MSY) (table 1). Fishing mortality in the western cod stock however was still three times higher than F_{MSY} in 2008, and has been classified as overexploited throughout the studied period (ICES 2009).

Table 1. Fishing mortality (F) and optimal level F_{MSY} leading to MSY in 2008.

2008	**F**	**F_{MSY} (ICES)**	**F in relation to long term yield**
Western cod	0.75	0.25	*Overexploited*
Eastern cod	0.25	0.3	*Appropriate*
Eastern herring	0.25	0.16	*Overexploited*
Bothnian herring	0.15	0.19	*Appropriate*

Herring in the eastern Baltic region was classified as overexploited in 2008, as the fishing pressure was almost the double of F_{MSY} but the Northern (Bothnian sea) herring was considered to be sustainably harvested, and the biomass tripled in the late 80's and has remained high with an "appropriate" fishing mortality below F_{MSY} (table 1) (ICES 2009). Cod and herring are interlinked by trophic predator-prey interactions in the Baltic Sea, which also involves sprat (*Sprattus sprattus*), and the whole ecosystem has been characterized by fisheries induced regime shift from cod to clupeid dominance since the early 1990:ies (Österblom et al. 2007).

Figure 2. A typical Swedish Baltic Cod trawler organized in The Swedish Cod Fishermen's' Producer Organization (STPO), an association of fishermen primarily fishing cod from the Baltic Sea. The producer organization is open to trawlers, gill-netters and long-liners. http://stpo.se/en/

3. Goal and Scope

3.1. Aim

The aim of this study was to evaluate novel approaches of biological impact categories in LCA, and demonstrate how LCA could be used to benchmark environmental performance of fisheries. As a case study we choose Swedish trawl fisheries in the Baltic Sea targeting major stocks of cod and herring.

To achieve this, we collected biological and technical data for 2008, and benchmarked these fisheries with novel and established impact assessment techniques. The temporal performance and applicability of key drivers (i.e. stock status, discards, swept seafloor area and fuel consumption) was also analyzed, and a sensitivity analysis of model choices was performed.

3.2. Scope

The study was carried out according to *ISO 14040, ISO14044* (ISO 2006a, b) with guidance of International Life Cycle Data system standard (*ILCD*) for Life Cycle Assessment (ILCD 2010). All details about the novel approaches in terms of impact assessment see section 4.

The functional unit (i.e. the product to be studied) used to compare the different products was one kg edible fish product landing at port, which requires 2.44 kg of round cod per kg edible yield compared to 1.63 kg of herring, due to different filleting yields (Winther et al. 2009). This unit reflects the function of providing society with protein, as the two species have a similar protein content (16% resp. 18%) (Livsmedelsverket 2012).

The basis for co-product allocation, i.e. the distribution of upstream burden on co-products coming out from the same process, was mass allocation because this was seen as the most transparent and relevant method. The importance of this choice is discussed in a sensitivity analysis. It is also important to recognize that we placed the entire burden from the fishery on the edible product, i.e. assumed no use of by-products, in this step translating impacts from the fishery to a more comparable unit.

The data included in the model consisted of a foreground system consisting of four inventory areas: 1) target catch sustainability 2) by-catch/discard, 3) swept trawl area 4) combustion, and a background system based on literature values (fig. 4).

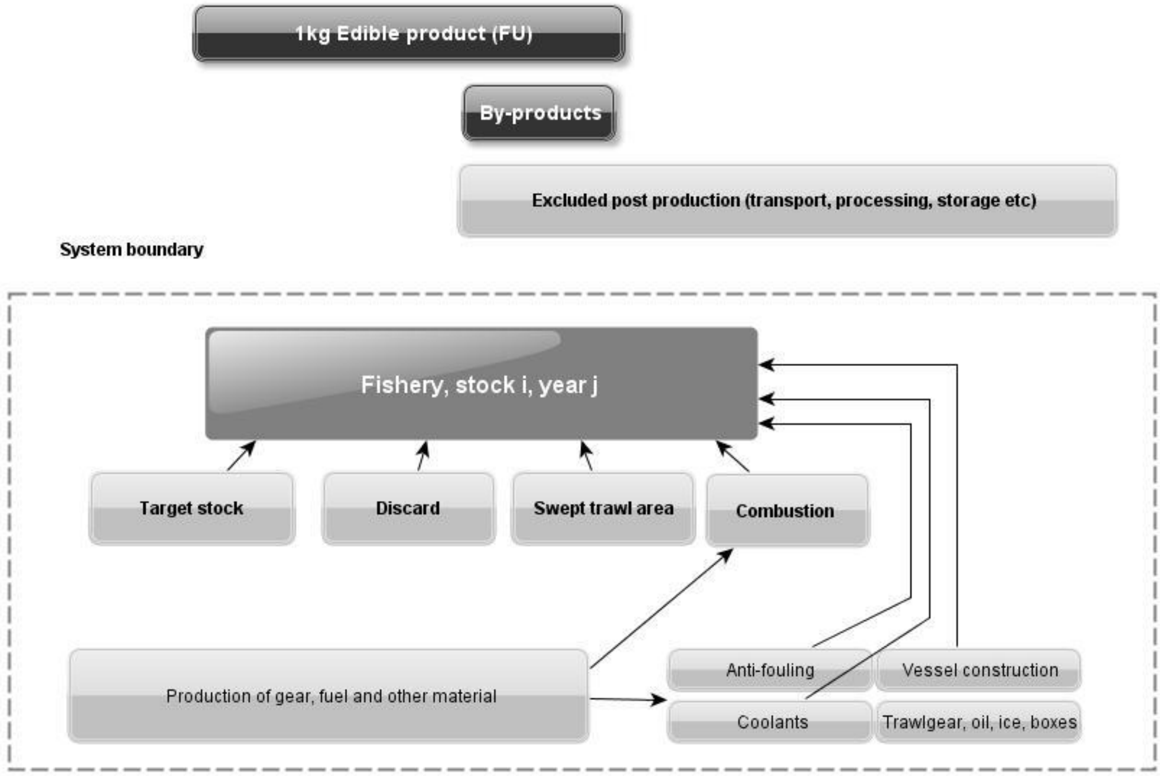


Figure 3. Flow chart of the fishing systems studied following the functional unit (FU) of one kg of edible fish for each stock *i* and year *j*. Prioritized inventory datasets are marked in bold font.

The background system consists of literature data on cooling agents, antifouling, nets, oil, ice, plastic boxes and capital goods (boat construction and maintenance) from the Ecoinvent LCA database (Ecoinvent 2007) including uncertainties and published seafood LCAs. These datasets are only available per species group, however, not per stock or year.

The subdivision into foreground and background system reflects the findings in previous LCAs of cod and herring from the same region. (Ziegler et al. 2003; Thrane 2004; Ramos et al. 2011). Four main model choices were tested in a sensitivity analysis to evaluate the impact of modeling choices: (I) Lost Potential Yield [choice of characterization model and time perspective], (II) Allocation of mixed catch on fishing boat [mass / economic], (III) Missing post-landing chain. (IV) By- products used [mass /economic].

4. *Novel impact assessment*

The following section covers all novel impact categories used in the case study, the inventory required, reflections about applicability and some aspects of verification.

To put the novel approaches in an context we used ReCiPe 1.04 midpoint hierachist version (Goedkoop et al. 2009) in the dedicated LCA software SimaPro 7.3 (PRé-Consultants 2011) including all 18 default impact categories.

The total set of midpoint impact categories was priority grouped as High, Medium, Low or Very Low by the authors, based on expert judgments. Aspects taken into account were:

(1) relevance of environmental impact from a fishery management perspective

(2) occurrence in the defined foreground system with high quality input data

(3) relative magnitude of emissions though normalization and endpoint characterization following an iterative LCA approach (Table 2).

Table 2. Impact categories used in case study divided into traditional (emission) impact categories and new or revised biological impact categories (subdivided into target stock and ecosystem effects)

Priority group	***Type of impact***	***Impact Category***	***Unit***	***Comment***
High	Target stock	**Overfishing through Fishing mortality (OF)**	kg "F_{MSY} excess exploitation equiv."	In press, post revision. Fishery specific impact category
High	Target stock	**Overfishedness of Biomass (OB)**	kg "(B_{MSY}) Lost Potential Yield equiv."	In press, post revision. Fishery specific impact category
High	Target stock	**Lost Potential Yield (LPY)**	kg "(Projected average) lost potential yield equiv."	In press, post revision. Fishery specific impact category
High	Ecosystem	*Total discard*	kg discard	Fishery specific impact category
High	Ecosystem	*Seafloor impact*	m^2 seafloor area swept	Fishery specific impact category
High	Ecosystem	*Primary Production Required*	kg carbon appropriated	Fishery specific impact category
High	Emission	Climate change	kg CO_2 eq	ReCiPe midpoint Hierachist
Medium	Emission	Ozone depletion	kg CFC-11 eq	ReCiPe midpoint Hierachist
Medium	Emission	Terrestrial acidification	kg SO_2 eq	ReCiPe midpoint Hierachist
Medium	Emission	Marine eutrophication	kg N eq	ReCiPe midpoint Hierachist
Medium	Emission	Photochemical oxidant formation	kg NMVOC	ReCiPe midpoint Hierachist
Medium	Emission	Particulate matter formation	kg PM10 eq	ReCiPe midpoint Hierachist
Medium	Emission	Marine ecotoxicity	kg 1,4-DB eq	ReCiPe midpoint Hierachist
Low	Emission	Human toxicity	kg 1,4-DB eq	ReCiPe midpoint Hierachist
Low	Emission	Ionising radiation	kg U235 eq	ReCiPe midpoint Hierachist
Low	Emission	Freshwater eutrophication	kg P eq	ReCiPe midpoint Hierachist
Low	Emission	Terrestrial ecotoxicity	kg 1,4-DB eq	ReCiPe midpoint Hierachist
Low	Emission	Freshwater ecotoxicity	kg 1,4-DB eq	ReCiPe midpoint Hierachist
Very low	Emission	Water depletion	m^3	ReCiPe midpoint Hierachist
Very low	Emission	Metal depletion	kg Fe eq	ReCiPe midpoint Hierachist
Very low	Emission	Fossil depletion	kg oil eq	ReCiPe midpoint Hierachist
Very low	Emission	Agricultural land occupation	m^2a	ReCiPe midpoint Hierachist
Very low	Emission	Urban land occupation	m^2a	ReCiPe midpoint Hierachist
Very low	Emission	Natural land transformation	m^2	ReCiPe midpoint Hierachist

The impact on target stocks where quantified in three different ways, all relating to MSY reference points and aggregated stock status data which are described in detail in (Emanuelsson et al. submited 2013). Primarily, we estimated the **Lost Potential Yield (LPY)** for each fishery by a iterative function of current exploitation rate and state of stock projected (20 years) where current exploitation rate is compared with a scenario of stopped fishery until the biomass reaches full reproducing capacity (B_{MSY}). This model is complemented with a simpler model using MSY-L as a static reference in the sensitivity analysis.

Note however that this method in currently undergoing revision and publication process. In the previous interim reports of the LC-IMPACT project and the oral contribution at LCA-FOOD Conference in Saint-Malo 2012, we called the draft version of the impact category "Wasted Potential Yield (LPY)", however after internal reviewer comments we changed the name.

The main principles of Lost Potential Yield are also explained by two sub impact categories of Overfishing through Fishing mortality ($F/F_{MSY}-1$) and Overfishing of Biomass ($B_{MSY}/B-1$) defined by ratios to the reference point and complemented with a normalizing term (-1) to harmonize with other emission categories (that are zero when no environmental harm is caused and increase with increased environmental harm).

Total discard (TD): Commonly expressed as the ratio of discards in the total catch, in LCA it is typically calculated as mass units of discards per kg of landing (Hornborg et al. 2012).

Swept Area (*SA*): Potential area impacted by bottom trawls, calculated as effective trawl width (in this case the full distance between the trawl doors including bridles) multiplied by the average speed giving an area swept per trawl hour and the divided by the landings during the same time period (Nilsson and Ziegler 2007).

Primary Production Required (*PPR)*: Estimated from the trophic levels of the landed and discarded species and measured in kg fixated carbon required per kg of landing (Hornborg et al. 2012).

Additional aspects of threatened fish species according to the IUCN **Red List (VEC)** were considered qualitatively but excluded from the selection mainly due to insufficient resolution of data.

4.1. Target catch (Lost Potential Yield methodology)

Used quantitatively. A target stock effect.

The Lost Potential Yield characterization and complementing "sub-impact categories" Overfishing through Fishing mortality and Overfishing of Biomass function was preliminary applied with a main conclusion about resource overfishing being generally larger in both cod stocks than the herring stocks, however the method framework was then revised with **more accurate Fmsy input data directly from ICES 2012** (not the literature source Froese et al 2010). The updated results indicate shift in the conclusion where the ranking shifted so that the best performing herring actually exceeded the worst performing cod – thus emphasizing the need to consider stocks rather than species even more than previously.

The first versions also indicated an unrealistic assumption about "instantaneous fishing mortality" (as measured on a log scale and communicated by ICES), which should not have been a direct input to the year discrete Schaeffer surplus production function. Instead a log transformed input of fishing mortality was suggested by the external reviews. This slightly lowered all LPY scores of the case study when implemented with no shift in ranking, although the worst performing years of the worst stocks decreased proportionally more than the average. Thus, taken together this altered the conclusion about Eastern Baltic cod and herring than in the first version favored herring as a species over the two stocks in despite of the latest Fmsy values from ICES.

4.1.1. Inventory

All stock assessment data were obtained from the ICES stock summary database regarding the years 2002-2008 (F, SSB, L) (ICES 2011a) and reference points for maximum sustainable yield (FMSY, BMSY and MSY) were obtained from Froese and Proelß (2010) who calculated their values based on three modeling approaches; 1) a demographic yield per recruit analysis 2) a surplus production analysis and 3) a stock recruitment analysis (Froese and Proelß 2010). These calculations used data originating from ICES 2008 and were intended to be updated every five years (Froese et al. 2011).

To retrieve the stock summary database a practitioner could use the direct links at ICES homepage (http://ices.dk/datacentre/StdGraphDB.asp) or obtain them from the short ICES advice communication or the background "Working group reports", which all can be retrieved from the ICES website.

The reference values from Froese and Proelß are directly accessible (http://eprints.uni-kiel.de/8459/1/faf_349.pdf) and could be directly exported from the public supplementary information provided by the publisher (http://onlinelibrary.wiley.com/doi/10.1111/j.1467-2979.2009.00349.x/suppinfo).

Gaining access to these type of data has not been a problem, however since several different values exist based on which assessment and which year it was finalized, this can still be quite a challenge.

Also it could be debated if the “stocks x, year y” should be regarded as the ”formal inventory substance”, or if actually the main input of fishing mortality F, spawning stock biomass SSB and reference values Fmsy and Bmsy (i.e. SSBmsy) should be considered the true inputs to the LCA model. In our case the same authors contributed to various extents with both method and application and these issues became more philosophical, although it was concluded that the necessary spatial and temporal resolution would be each stock at the most relevant year, which in practice sets a very high demand to updating frequency of published characterization factors if though to be included in typical LCA databases, however some species aggregated groups using average values of a certain amount of years could probably still be useful in traditional LCA databases for outlining some general differences in cases were traceability (or the lack of) hinders the most accurate use of stock and years specific impact assessment.

4.1.2. Application

To apply any of the methods in the LPY framework the user have to choose which reference year to collect data from. Each year ICES runs the main stock assessments models in multinational working groups with a new time series entry of survey data, landing data and discards. This actually increases the accuracy of historical biomasses since more recent data have been fitted to the time series which model the abundance of every age group. This means that every value of F and SSB is updated each year even when it regards the same year, for example 2002 data. The final stock assessments and advice are typically published according to a specific schedule, for the Baltic Sea stocks this is typically in May as an example (see time t) in table 3.

ICES include the previous year’s biomass and fishing mortality and a preliminary assessment of the current year based on the politically decided total allowable quotas that have been established for the previous year (see table 3 again). However the Stock Summary Database lags behind two years (which was the reason we choose 2008 as the most "recent year" at start of the LC-IMPACT project in 2010. These retrospective data are also more consistent and less inclined to change over time as the most recent or even more the preliminary assessment.

It is possible to base LPY on the each of these entries. Also ICES projects one year ahead with different F-scenarios to support decision making, which would be a true forecast based on the best available model (the projection in LPY characterization model should rather be seen as a process of relative comparison of input parameters in a well-established simplistic biological model, not a biomass forecast in the true sense.

In practice this could be confusing and require some prior knowledge about stock assessment or guidelines. Based on this first attempt, we recommend type 1 retrospective data that could be obtained directly from ICES database etc.; however it would be interesting to see applications of forecast in LCA.

Table 3. Input data types (F and SSB) into LPY characterisation

Input data type (F, SSB)

t-2	Final SSB and F accessible in Stock summary database	**Type 1 data (Retrospective analysis)**
t-1	Final SSB and F from in ICES Advice 2012 and Working group documents	Type 2 data (Previous year)
t	**Target year for LPY and LCIA data, ex 2012, published according to a stock specific schedule.** Preliminary SSB and F from TAC, described in 2011 assessment	Type 3 data (Current year)
t+1	F and SSB scenarios as advice (best available model)	Type 4 data (Projections)

4.1.3. Verification

For the Baltic case study the Marine Stewardship Council (MSC) certified three national fisheries of Baltic cod from the eastern stock in 2010, this correlates well with a large drop of LPY in 2009 dataset due to reductions in fishing mortality, see figure 3 a and b. The stock is still below BMSY although the MSC has motivated the labeling with that the F will lead to increased SSB (which also is demand for continued certification(Gutiérrez et al. 2012).

A similar observation could be seen in Portuguese sardine fisheries when the MSC-label was suspended in 2010, mainly due to low recruitment but also followed by changes in fishing mortality and spawning stock biomass.

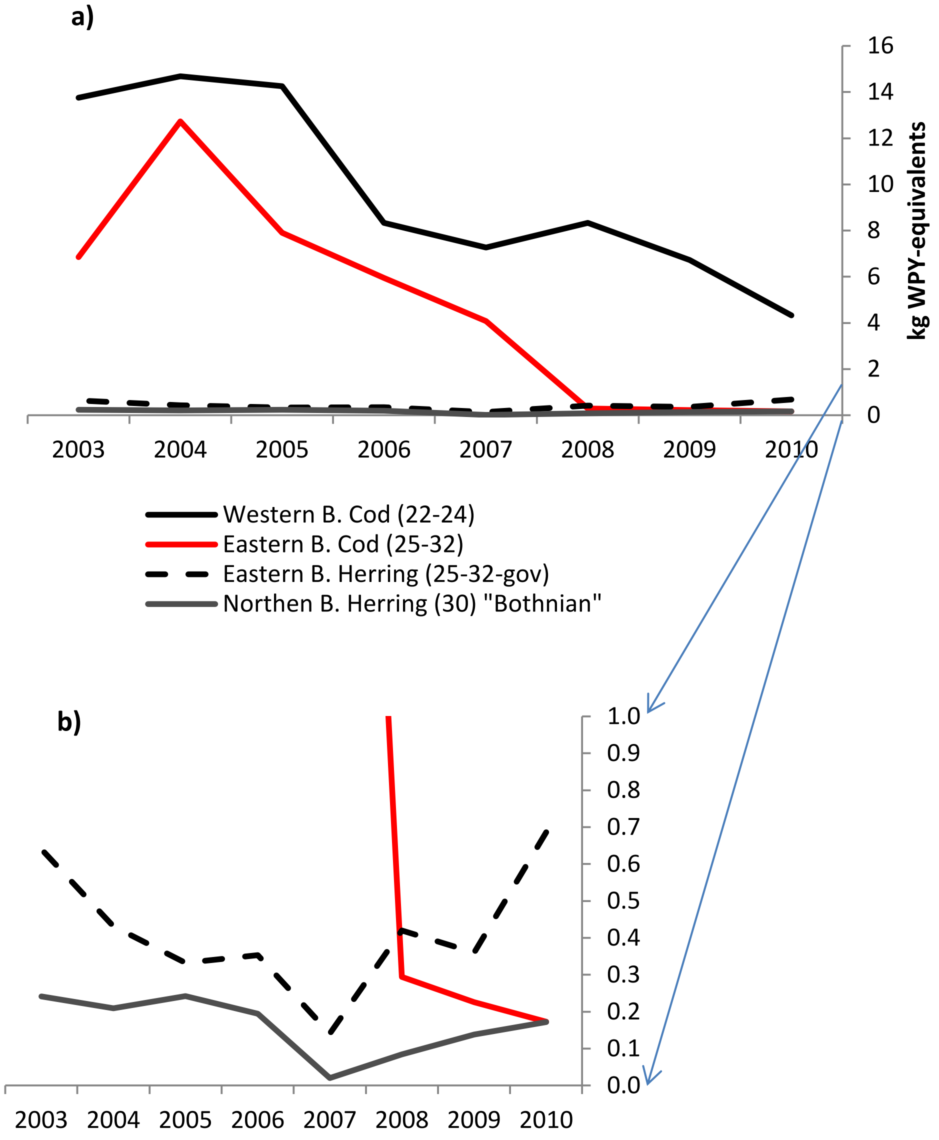


Figure 4. Lost Potential Yield results between 2003 and 2010 with peaks above 10 kg wasted potential future yields per kg landed in a). Zoomed in to below 1 kg wasted per landed kg in b)to highlight that three fisheries from the Eastern Baltic Cod (red) where MSC labeled in 2010, based on the 2009 data (i.e. after two years of LPY > 0.3).

In the end, overexploitation of marine species will be influenced by a multitude of ecological parameters not included in an LCA. However F – a proportion of the mature stock that is killed by fishery, and SSB then biomass measurement of the reproducing stock, is by all means probably the two most important. As an example, for Eastern Baltic herring, it has been concluded in the publication *"The beauty of simplicity"* that series of ecological factors were actually working against the Baltic cod, which is sensitive to temperature and inflows of saline waters in the Baltic sea, yet it has substantially improved since fishing mortality dropped from 1.46 in 2004 to below 0.3 (approximately the Fmsy in 2008) and forth (Cardinale and Svedang 2011).

4.1.4. Interpretation

The LPY value should from a fishery management context be viewed as a quick index to compare stocks primary in terms of future resource availability. To interpret it however, the two rations of F/Fmsy and B/Bmsy are key components which are also frequently used in the discussion about sustainable fisheries. Defining Overfishing through Fishing mortality and Overfishing of Biomass as inverted and scale adjusted versions of this was found a little bit impractical to work with, although potentially valuable as a second hand choice if LPY algorithms for pre-calculated CF are not available. Even though we for the sake of this study and its exploratory value used all of them, the LPY could as well be discussed qualitatively only by the F/Fmsy ratio (as a factor) and the B/Bmsy values (in percentages).

However, the future projections should be used with great caution, since the primary aim of the method is to compare the potential of overfishing between stocks (i.e. relatively), which is seems to do satisfactory; the final numerical values are not easily verifiable and thus of lesser relevance. A typical misuse could be to calculate the time until fishing collapse, or use it without reviewing the latest stock advice; the data and metadata found in the original assessment.

Typically LPY can increase the knowledge about some general aspects for a fishery, but many local unique features should be qualitatively discusses as well. As an example, the average sizes of cod in the Baltic sea is still alarmingly low rendering lower prices and corresponding to a lower reproductive potential since larger cods typically produce larger amount of eggs with higher reproductive quality.

4.2. Total discards (TD)

Used quantitatively. **An ecosystem effect.**

Total and unspecified discards have prior been used in several seafood LCAs either as total discard per landing or as a total discard related to a normalizing global factor (Vázquez-Rowe et al. in press; Parker 2012). This case study uses two approaches of characterizing the different discarded. In the end however, after having analyzed the species composition, only one of these approaches was applied (table 3, Eastern Baltic cod, and table 4, Western Baltic cod) but complemented with unspecified total discards.

The largest practical problem here concerned statistical representatives, as the Western Baltic Cod fisheries was severely under-sampled compared with the fisheries on Eastern Baltic cod. To be able to robustly assess a significant difference between the two areas was not possible and we were pushing the borders of what is acceptable only by comparing the total discard values (71% and 74% respectively). To further assess potential differences in the impact potentials attributed to separate discard compositions, i.e. to state that the characterized species compositions would give us more information, would clearly have been an exaggeration of quality of these results, since rare species are less common in the smaller sample.

Table 4. Landings and discard values in the Eastern Baltic stock from the national survey program based on Swedish boats between 2003-2007

Eastern Baltic Cod

(85 survey hauls 2003-2007)

Landings	**Swedish Red List 2010**	**International Red List (2010)**	**Quantity (kg)**	
Gadus morhua	**EN**	**VU**	85171823	**98.77%**
Pleuronectes platessa	**LC**	**LC**	433160	0.50%
Melanogrammus aeglefinus	**EN**	**VU**	360755	0.42%
Platichthys flesus	**LC**	**LC**	129792	0.15%
Psetta maxima	**LC**	**NE**	55224	0.06%
Salmo salar	**LC**	**LC**	25960	0.03%
Glyptocephalus cynoglossus	**LC**	**NE**	16640	0.02%
Merlangius merlangus	**VU**	**NE**	11016	0.01%
Merluccius merluccius	**NA**	**NE**	9435	0.01%
Conger conger	**NA**	**NE**	8000	0.01%
Microstomus kitt	**LC**	**NE**	4160	0.01%
Pollachius pollachius	**CR**	**NE**	3330	0.00%
			86230295	
Discards				
Gadus morhua	**EN**	**VU**	12087470	**74.40%**
Platichthys flesus	**LC**	**LC**	3504570	21.60%
Pleuronectes platessa	**LC**	**LC**	386470	2.40%
Pollachius virens	**LC**	**NE**	150000	0.90%

Clupea harengus	LC	LC	34010	0.20%
Melanogrammus aeglefinus	EN	VU	22000	0.14%
Psetta maxima	LC	NE	15850	0.10%
Alosa agone	NA	VU	9350	0.06%
Merlangius merlangus	VU	NE	8750	0.05%
Sprattus sprattus	LC	NE	8200	0.05%
Limanda limanda	NA	LC	5180	0.03%
Scomber scombrus	LC	LC	4080	0.03%
Hippoglossoides platessoides	LC	NE	3500	0.02%
Molva molva	EN	NE	3000	0.02%
Merluccius merluccius	NA	NE	1800	0.01%
Glyptocephalus cynoglossus	LC	NE	700	0.00%
Microstomus kitt	LC	NE	600	0.00%
Myoxocephalus scorpius	LC	NE	340	0.00%
Cyclopterus lumpus	NT	NE	300	0.00%
Scophthalmus rhombus	LC	NE	300	0.00%
Eutrigla gurnardus	NA	NE	120	0.00%
Trisopterus minutus	LC	LC	110	0.00%
			16246700	

Table 5. Landings and discard values in the Eastern Baltic stock from the national survey program based on Swedish boats between 2003-2007

Western Baltic Cod

(14 survey hauls 2004 and 2006)

Landings

Gadus morhua	EN	VU	12295446	**99%**
Pleuronectes platessa	LC	LC	113060	0.90%
Platichthys flesus	LC	LC	34824	0.30%
Salmo trutta	LC	LC	5405	0.04%
Limanda limanda	NA	LC	4664	0.04%
Psetta maxima	LC	NE	4368	0.04%
			12457767	

Discards

Gadus morhua	EN	VU	1717900	**71%**
Platichthys flesus	LC	LC	613400	25%
Pleuronectes platessa	LC	LC	68350	3%
Limanda limanda	NA	LC	9190	0.40%
Merlangius merlangus	VU	NE	1950	0.08%
Microstomus kitt	LC	NE	400	0.02%
Enchelyopus cimbrius	DD	NE	150	0.01%
			2411340	

Figure 5. A typical filled “cod-end” (the end of the trawl) after some hours of trawling, note the relatively clean catch dominated by cod. Photo: STPO

4.2.1. Inventory

Species specific discard data of cod fishery was obtained from the Swedish Board of Fisheries monitoring program on-board Swedish vessels, covering 38 hauls in the eastern area and 14 hauls in the western area; in total 123 hauls for the whole times series analysis of the Eastern stock between 2003-2008. Discard data for the herring fishery are not monitored regularly, but assumed to be low; here approximated by data from a Swedish sprat fishery which had an average discard rate of 0.02% (Walther 1995).

4.2.2. Application

The typical way of communicating discards are by the rate r (discarded mass per total catch) as in the latest global assessment of discards which also could be used as reference levels for discussion (FAO 2005).

But for LCA purpose it is more useful and logic to relate the rate to it to the corresponding mass flow of the functional unit. For seafood LCAs this typically done by a conversion factor so that the midpoint indicator is measured in discarded mass per landing, see equation 1:

Equation 1 – Discards per landing converted from the rate r discards per total catch

$$D\_LCA = \frac{r}{1 - r}$$

4.2.3. Interpretation

There are clearly more problems with discards in the cod fisheries than in the herring fisheries in the studied area. The levels are also relatively high compared with a baseline noted in a global FAO assessment (FAO 2005). There seems to be a pattern of higher discards in the Western cod stock fisheries, which is also concluded from the assessments of total discards of cod from all countries made by ICES, which is the main contributor to the observed amounts. The inventory data from Swedish boats can barely support this, which has consequences for the possible interpretations that could be made from assessing discards in terms of VEC and PPR. However, as the rates at least not seemed contradictive in trends relative to ICES assessment of total discards, we based the LCI data on the actual Swedish survey data.

Table 6. Reference discards rates, a) sensitivity analysis of difference between eastern and western cod stocks b) comparison with global values from (FAO 2005)

a) Dominance test cod stocks	*Discards - per catch (FAO)*		
	Western	**Eastern**	**W>E**
FiV 06 (main scenario)	29%	24%	1.32
FiV_allyears	27%	19%	1.55
ICES_extrapol 2006	15%	7%	2.37
ICES_extrapol_all years	13%	6%	2.0

b) Global reference (FAO 2005)	per catch	per landing	per edible part (Cod)	per edible part (Herring)
Cod Baltic SE 2003-2008 Pooled	*19%*	*0.16*		
*Cod West 2006**	*20%*	*0.27*	*0.66*	
*Cod East 2006**	*16%*	*0.19*	*0.47*	
Global average	8.0%	0.09	*0.21*	0.14
North east Atlantic	13%	0.15	*0.36*	0.24
Demersal finfish trawl	9.5%	0.10	*0.26*	0.17
Midwater (pelagic) trawl	3.4%	0.04		0.06
Small pelagics purse seine	1.2%	0.01		0.02
Herring (approximated by sprat 1995)	0.02%	0.0002		0.0003

4.2.4. Threatened fish species in discards (VEC)

Not included quantitatively in the case study, but qualitatively discussed. An ecosystem effect.

The Baltic Sea is a relatively species poor ecosystem, and the fisheries are in general more "clean" in terms of amounts and species diversity of discards. In other ecosystems, mixed fisheries pose a great constraint to the successful rebuilding of fish stocks (Hutchings, 2000), as it is unavoidable to catch depleted fish species when targeting other species. In these more species rich areas, studying the amount of sensitive and depleted fish (VEC) that is discarded per kilo landing could be useful to account for discarding impacts, as has been found in the Norway lobster fishery on the west coast (Hornborg et al., 2012). There is however some unavoidable constraints with the VEC approach:

4.2.5. Inventory

In general, quantitative information on species composition in discards is very restricted. In a few cases, individual counts are available (which is preferred), and at best, species mass can be found (which could still prove to provide useful information, see Hornborg et al., in prep 1). Still, in most cases, discard data will have to be collected by inventory by the LCA practitioner for VEC to be applied. In the case study, this data was however available but not with a resolution enough to support quantitative based conclusions from it. Also, the clear differences found between cod and herring fisheries could be communicated just as well only based on total discard rate values.

4.2.6. Application

In practice, a practitioner must by himself/herself consult the national and international Red Lists (i.e. to construct the CF) since the assessment of fish by the IUCN Red List Categories and Criteria is on-going. However, species complexes that are considered to be most vulnerable to fishing (e.g. with limited distribution range such as groupers, or slow growing species like rays and sharks) have been fully assessed. In the case study, all species included had been assessed by the national Red List and some also by the global Red List.

When comparing fisheries in different regions, one fishery can have all occurring fish species assessed nationally with the IUCN Red List Categories and Criteria (the situation of the case study) whereas the other fishery might only have a minor fraction of the species caught assessed, possibly only by the global Red List framework. The national Red List is considered to be preferred to use, as the accuracy is better the closer to stock status as possible (which the regionalized list usually best provides) (Hornborg et al., in prep.). It should be noted that regional threat status is likely to give a higher threat status, as it has been stocks, not species, of fish that have been locally extirpated (Reynolds et al., 2005). Still, there are exceptions to this, such as the Atlantic cod stock from the Barents Sea, which is plentiful, and could not be considered as threatened in Norway; in this case, the global Red List would be most inappropriate to use as Atlantic cod as a species is considered to be Vulnerable.

The same situation applies for the case study, where the cod came mainly from a stock that is considered to be sustainable managed today (but not in the start of the time series). Still, the assessment by the Red List is at species level, and the different stocks have been pooled together, which result in cod as a species have the status of Endangered. This made it difficult to consider cod in discards to be applicable to VEC. It should still be noted that even if the situation of the Eastern Baltic cod stock has improved in recent years, this does not imply that the situation for this cod stock in the Baltic is not problematic, as e.g. the habitat range has decreased considerably over time. These discrepancies between stock status and species status were identified already in the method paper (Hornborg et al., in prep 1). It could be argued, that as cod is not a data deficient species, target stock methods could be used instead, as VEC was intended to primarily grasp those species that lack biological reference points.

4.2.7. Interpretation

The greatest reason for not applying VEC was due to the goal and scope of the study, which was to benchmark and relatively compare the differences between the four fisheries by midpoint impact assessment. As the inventory data displayed such a large dominance of cod, it was not considered to be relevant to quantitatively display the differences only in terms a few percentage more or less cod in the catch ratio. Also, the lack of data points could statistically make the distinction between Eastern and Western stock even more questionable in terms of total mass, and to take this one more step by stating that both also were different in catch composition was not found to be feasible.

This however, does not diminish the potential benefits of using VEC, which has been demonstrated in another case study of the Norway lobster fishery of the Swedish west coast (Hornborg et al., 2012). Here the discards are proportionally greater and more divers. As we see it, checking for VEC species I catch or bycatch should be one of the default strategies when assessing which relevant flows to include in seafood LCA studies. However, as with any impact category, it may be considered not relevant to include in some situations, but then it should be qualitatively motivated in the LCA instead of quantitatively assessed.

It should also be noted that the Swedish Red List is updated every five years, which calls for careful attention to changes in species threat status. As for the global Red List, this is done continuously, which also should be considered.

4.3. Primary Production Required (PPR)

Used quantitatively in the case study. An ecosystem effect.

PPR was applied for discards and target catch combined, to indicate total disturbance of the ecosystem, which is one of the dual conceptual damage pathways that have been described in WP1. The other one is general resource limitation, which is not found applicable in the highly eutrophicated Baltic Sea area.

It could be argued that an overlap with target stock impact categories then exists, and that these impact categories only should be used for by-catches. However, we concluded that it does not make sense to omit the main contributor (the cod at a high trophic level) if we want to draw any conclusions about the overall impact on ecosystem or production limitations. Also, this is more directly aiming at the Area of Protection Natural Environment, which LPY is not directly targeting. In the end, a practical approach to seafood specific impact categories might be to deal with multiple indicators to support the best available final qualitative conclusions.

4.3.1. Inventory

Trophic level data was obtained from FishBase for all target and by-catch species (Froese and Pauly 2011). Note than many different ways to estimate trophic levels exist, some of them are derived from stomach analysis with a spatial resolution, and the uncertainties are in general quite large. This might be a problem if too much conclusions are based on any comparison between two taxa, and careful attention should be paid to proper trophic level- and transfer efficiency values. We used the average values on a species level which provides a fair comparison for the assessment of the big picture, either disturbance in the food web or in terms of limits of total biotic production if relevant.

It should also be noted that it has already been discussed how separate PPR values could be interpreted in different ecosystems (Hornborg et al., in press). One factor is which value to use for transfer efficiency in the characterization function, which translates the trophic level into the PPR-value measured in sequestrated carbon. However, we used the standard global average of efficiency (10%) in this case study, as the aim was to compare fisheries within the same Eco-region (such a bias would have been relative and not affecting the rank)

4.3.2. Interpretation

First, the Baltic Sea is highly eutrophicated, so PPR could not be considered to be a matter of resource limitation; nutrient removal could instead possibly be a positive feedback. In other marine ecosystems, such as in the open ocean, the primary production is lower and the %PPR that is appropriated by fisheries could be more constrained. Still, energy flows in marine ecosystems are more complex than it would be correct to assume that high PPR would undoubtedly be favorable in a highly eutrophicated ecosystem, as fisheries can disrupt energy flows in several ways (Baden et al., 2012; Frank et al., 2007). PPR could also function as a proxy for impact on top predators, a functional group which could play a key role in terms of regulating ecosystem structure and functioning (Estes et al. 2011; Casini et al., 2009). By studying PPR only from discards, high values would be an indication of resource waste in either case, as a high amount wasted could rarely be favorable. This approach has been shown to be of relevance in a case study of Norway lobster trawling on the west coast of Sweden, where PPR of discards illustrated the amount of top predators discarded per kilo landing (Hornborg et al., 2012).

To conclude, further refinement of the PPR concept is needed. There might be a need for using regionalized transfer efficiencies in the equation, but this must be carefully elaborated on before. It should also be noted that PPR has been used prior in LCA but as Biotic Resource Use (BRU). As the BRU concept is somewhat vague in terms specifying what is included, it is suggested to from now on be renamed for what it is, PPR.

4.4. Seafloor impact

Used quantitatively in the case study. An ecosystem effect.

The development of methodology concerning seafloor impacts of fishing has changed from developing a quantitative framework assessing seafloor impacts by overlaying habitats and communities impacted by high resolution fishing effort data to a more descriptive approach how seafloor impact assessment can be taken further in different situations.

Initially, it was proposed to advance the state of the art measure swept area by 1) basing the assessment of the swept area on high resolution data including satellite positioning and 2) overlaying the fishing effort data by spatial vulnerability layers derived from an online database, which was a way of assessing seafloor impacts of fishing that had been initiated (Nilsson & Ziegler 2007). To use a quantified value on the vulnerability/sensitivity/recovery of a biological community to fishing impact would be close to an endpoint.

Clearly, fishing does impact benthic communities, as has been described by a considerable body of literature consisting of local and regional case studies, but compared to assessing the impact on target stocks, there is much less quantitative data available on seafloor impacts.

Some attempts have been done to review these studies, to develop indicators from them and to meta-analyze them in order to draw conclusions on a more general level. However, the general conclusion is that there is a bias in the studies performed regarding some types of gear and habitats, and lack of others and also that the outcome is not always conclusive.

In practice, a measurement of assessed restoration time based on the Marlin database seemed initially promising as it benefited from applicability towards various marine interventions (different types of fishing and construction) and included detailed habitat data for the British Isles, habitats which are typical for a large part of the North Atlantic.

However, it was considered too time-consuming and risky to try to translate the British benthic habitats into more general North Atlantic ones. The final results would have involved the judgments of an expert panel. The online database also clearly states that the quantified values are not recommended for further use in other applications, as do most of the authors of reviews of seafloor impact studies. It seems to be a particularly difficult area for quantitative assessment and the conclusion from our side was to take a step back and present an overview over the issue and alternative ways one could take in quantifying these impacts, rather than a fully quantitative assessment methodology.

In relation to the case study in the Baltic Sea, which due to its brackish water is not a fully marine area with typical marine habitats (as already mentioned in the section about by-catch/discard), but rather comprises highly unique habitats and environmental characteristics, a method building on North Atlantic marine communities or habitats would not have been fully applicable. The approach taken in the case study was therefore rather to advance the estimation of swept seafloor area by using high resolution data on trawling from the VMS (vessel monitoring system) and trying to find representative data on both theoretical trawl dimensions as well as effective width when trawling.

4.4.1. Inventory or application?

Again a situation arose were it was not clearly defined what should be seen as “inventory data” and what would be the characterization function in a novel seafood specific impact category. One could argue that the actual inventory rather should be the time needed to fish a certain amount of fish, and more true basis for characterization would be a specific index composed by the fishing capacity of the vessel per unit of effort (time), the speed and the effective gear width. Clearly, changing any of these inputs will have a major effect on the resulting swept area per kilo landed. Independently of whether we call it inventory or characterization, the procedure of how to calculate the swept area also needs to be described and this is done in the following three steps:

4.4.2. Calculation procedure

To summarize, we calculated the trawl area fishing effort (hours) per kg from logbook data and multiplied effort with speed and approximated gear width to give the swept area, which is the way it has been done also previously. The new things added to this approach were….

The effective trawl width was assumed to be 145m in the cod fishery, which includes girdles and doors based on four randomly selected boats that were equipped with trawl opening sensors. The average trawling speed was estimated to 3.0 knots for cod trawlers and 2.8 knots for herring bottom trawlers, by analyzing data from the VMS system, filtered by location and speed to exclude steaming and harbor activities. Actually 10% of Swedish Baltic herring landings are landed by bottom trawls, even though it is a pelagic species. Other pelagic herring trawls have no bottom contact and are therefore assumed to cause no seafloor impact. The fuel consumption data was derived from a report published annually by the STECF (Scientific, Technical and Economic Committee for Fisheries), which provided fuel consumption and catches per segment of each EU countries fisheries (i.e. a combination of gear type and length class). These overall data were weighted according to boat and gear type in each fishery (JRC 2011).

Swept area for cod fisheries were calculated by multiplying three datasets 1) fishing effort derived from logbook data (length of trawl hauls in hours) 2) trawl speed obtained from VMS signals and 3) effective trawl width obtained from a telephone survey of randomly selected fishermen and qualitative trawl binder interviews.

Equation 2. Swept area

$$A = speed * width * time = a[knot] * b[m] * c[h] =$$
$$= 1852a * \left[\frac{m}{h}\right] * b[m] * c[h] = 1852 * abc\ [m^2]$$

Table 7. Swept area calculation

	Cod East	Cod West	Herring East	Herring North
Trawling speed	3.0	3.0	2.0	2.0
Contact width	154	154	89	89
Average duration h per kg (CPUE)	0.00376	0.00498	0.00065	0.00212
Total area	3217	4261	214	699
Total area per edible part	7850	10397	349	1139
Compensated for pelagic catches (Herring)			35	114
Reference values				
Ziegler 2002 (55 m^2; 2 knots)	1711	m2	4.2	7186
Nephrops (Hornborg 2012)				15-22 000

4.4.3. Technical calculation description

Step 1: Deployment time

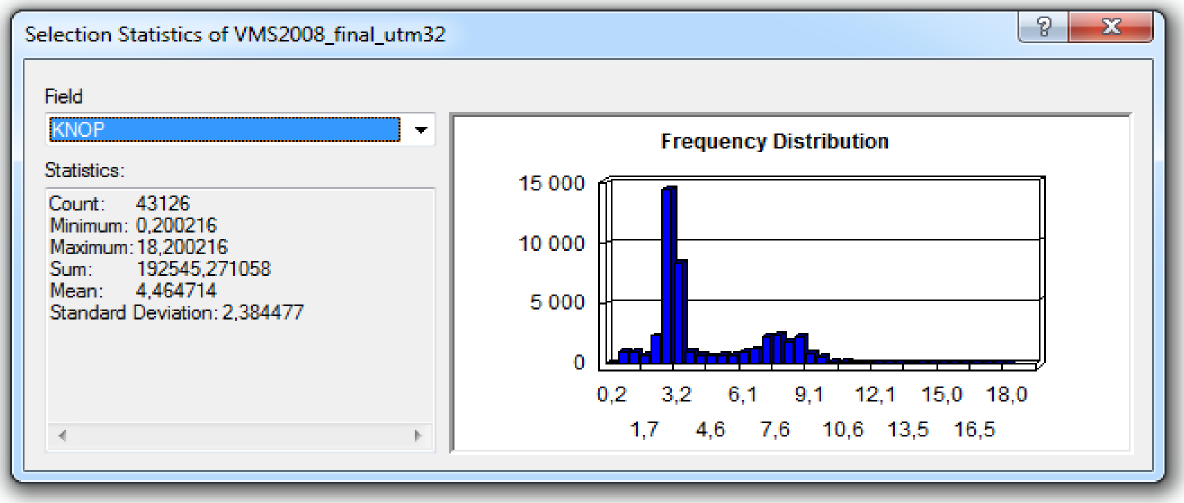
Table 8. Logbook data of total catch and gear deployment time filtered per area and metier (gear class)

	Total catch (kg)	Gear deployment (h)	time per kg (h)	time per kg (sec)
Bottom trawl for Clupeids				
Bothnian	1 092 499	2 316	**0.00212**	7.6
Eastern	14 326 248	9 296	**0.00065**	2.3
Bottom trawl cod				
Eastern	5 889 174	22 143	**0.00376**	13.5
Western	1 311 543	6 536	**0.00498**	17.9

Step2: Speed

Procedure in GIS software to filter out relevant speed:

1. Select relevant metier (see Table 5 for definition, in this case demersal Baltic trawl cod/ demersal Baltic trawl herring) from logbook dataset containing one entry per haul
2. Join with VMS dataset by trip id (res-id) . One position per hour including speed data
3. Remove outliers with negative speed or speed above 20knots (to facilitate visual analysis in GIS interface)
4. Visually analyze speed histogram 1: clearly the distribution is bimodal, where the first peak represents the most likely trawling speed somewhere around 3knots, and the second more diffuse peak represents the most likely steaming speed around 8 knots

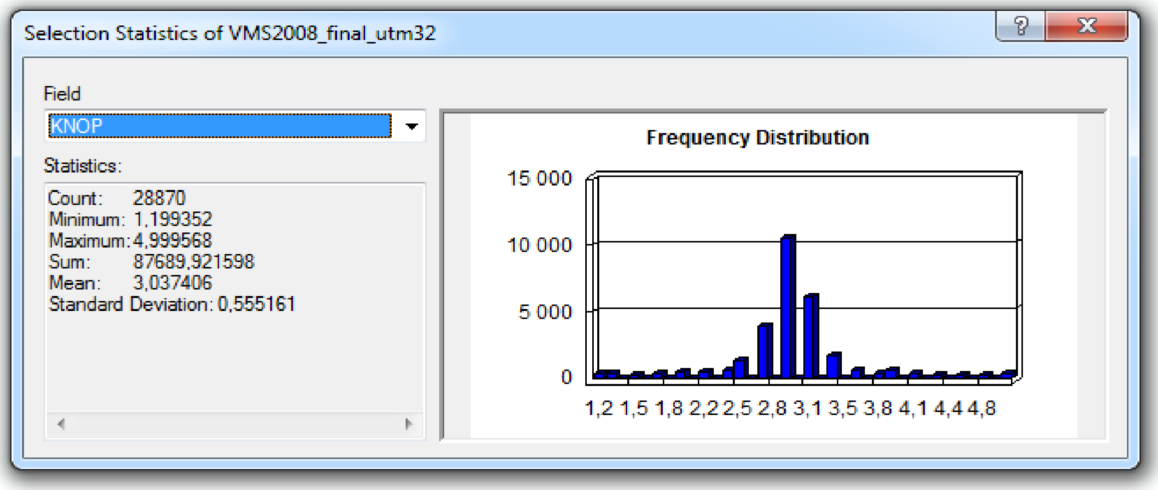


Field: KNOP

Statistics:

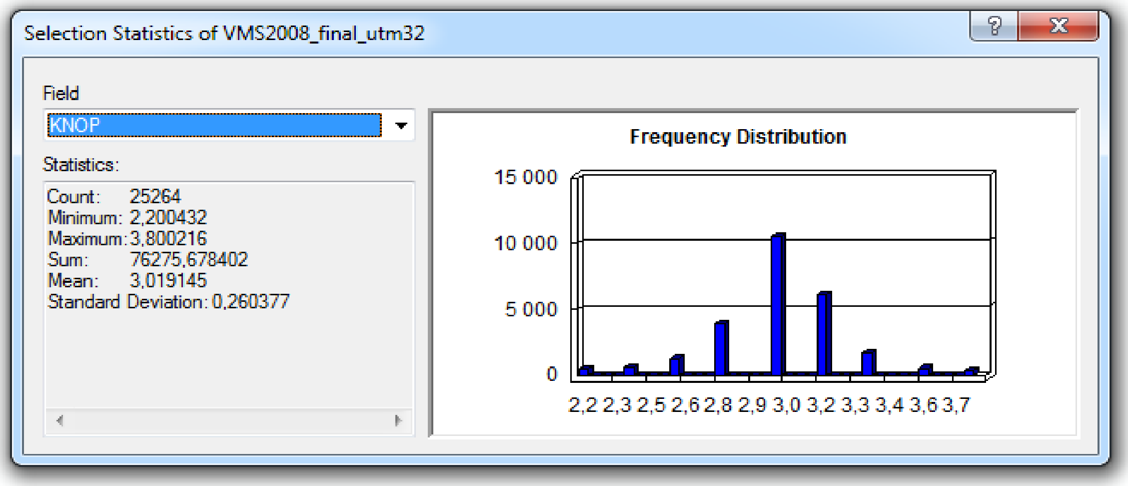
Count: 43126
Minimum: 0,200216
Maximum: 18,200216
Sum: 192545,271058
Mean: 4,464714
Standard Deviation: 2,384477

5. From this we removed all entries with speed below 1knot and above 4 knot to select refine the mean value based on the visual analysis and knowledge about typical fishing speeds for cod fisheries in the area.
6. Additionally removed entries closer than 3nm from harbor
7. Approximate average speed (assumed during trawling) as the mean of the most likely distribution iteratively narrowed in (see speed histogram 2 and 3).


Selection Statistics of VMS2008_final_utm32

Field
KNOP

Statistics:
Count: 28870
Minimum: 1,199352
Maximum: 4,999568
Sum: 87689,921598
Mean: 3,037406
Standard Deviation: 0,555161

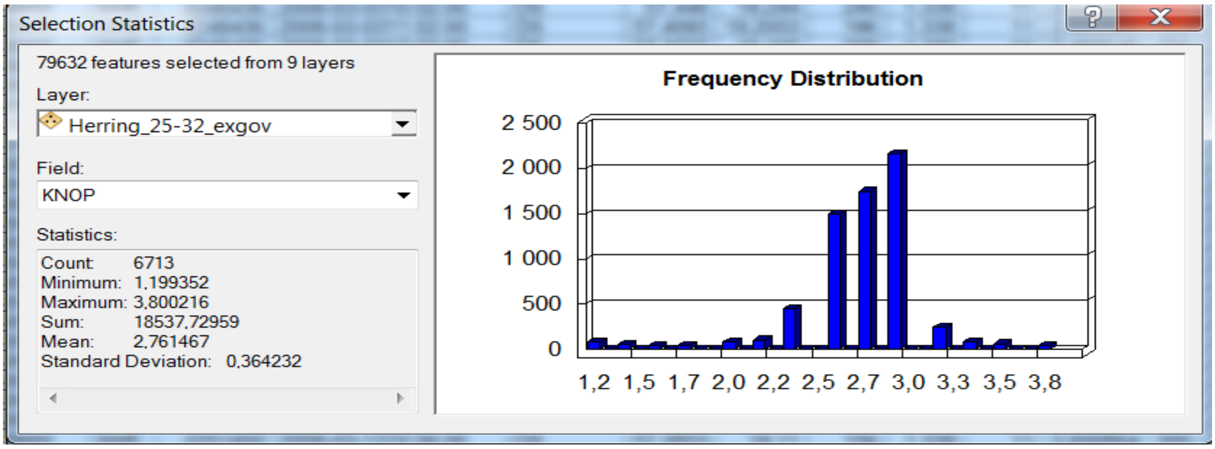

Selection Statistics of VMS2008_final_utm32

Field
KNOP

Statistics:
Count: 25264
Minimum: 2,200432
Maximum: 3,800216
Sum: 76275,678402
Mean: 3,019145
Standard Deviation: 0,260377

8. Hence, the most typical trawling speed for the cod fishery is assumed to be around 3.0 knots using the mean value of the selected data. The same procedure reveals no larger differences between trawling speeds when fishing the two different stocks and therefore this value is assumed valid for both fisheries.

   The clupeid bottom trawlers have a slightly lower average speed and were assumed to trawl at an average speed of 2.8 knots



Selection Statistics

79632 features selected from 9 layers

Layer: Herring_25-32_exgov

Field: KNOP

Statistics:

Count: 6713
Minimum: 1,199352
Maximum: 3,800216
Sum: 18537,72959
Mean: 2,761467
Standard Deviation: 0,364232

Step 3: Effective width (Door spread)

It is interesting to note that trawls, although highly regulated in terms of selectivity performance, are not standardized in any way in terms of design or operation. Hence any trawl is permitted as long as it delivers a catch of a certain composition and this makes it difficult to generalize seafloor impact calculations in terms of effective gear width.

Today many vessels are fitted with sensors that could accurately measure the trawl opening, while other have to be assessed from assumptions of the trawl door opening, based on attach angles and wires. In the case of Baltic trawling, a thesis worker from Gothenburg University conducted a telephone interview to approximate the door opening in various ways. In contrast to a previous assessment (Ziegler 2002) it was now found important to also include the connecting wires from otter boards as effectively in contact with the seafloor which almost doubled the effective with in the study. Such assumptions are however case specific and need to assessed separately for each case study (Thörn 2012).

Table 9. Randomly selected trawlers in Baltic Sea contacted by telephone interview during 2011 (from Thörn 2012).

	Apr. Door spread	*kW*	*Sensor*		Apr. Door spread	*kW*	*Sensor*
Herring 1	**60**	115	no	**Cod 1**	**125**	810	**Sometimes**
Herring 2	**88**	448	**yes**	**Cod 2**	**155**	500	**yes**
Herring 3	**128**	660	no	**Cod 3**	**120**	293	no
Herring 4	**80**	280	no	**Cod 4**	**180**	390	**yes**
Average	**89**			Average	**145**		
SD	28			SD	30		
n	4			n	4		
min	**61**			min	**115**		
max	**117**			max	**175**		

5. Life Cycle Inventory (LCI)

This section covers mainly the fuel emissions and background dataset, since the LCI data required for the novel impact assessment methods have already been covered in section 4.1- 4.4.

1.1 Fuel

Fuel use has been demonstrated a common hot spot for wild caught fish products in terms of emissions based impact categories (Ziegler et al. 2012; Vázquez-Rowe et al. 2012; Tyedmers et al. 2005). Thus, this was a prioritized foreground dataset together with the biological inventories covered in section 4.

To assess the fuel consumption per fishery, we choose a two-step top down approach, using data on fuel efficiency collected by the Joint Research Centre of the European Union (JRC) in the “Annual Economic Report on the European Fishing Fleet 2010” (JRC 2010).

In short, we first allocated national gear specific fuel consumptions to match the gear composition per species in the studied fleets (step 1), in the case of similar gear (cod fisheries) we added a step 2; allocating the fuel consumption according to the catch per unit effort ration, under the condition that the two fleets were actually technologically similar.

Note that a separate spread sheet had to be separately ordered from JRC to perform all calculations in this section (JRC 2011)

5.1.1. Fuel use per species

JRC annual report (JRC 2010) provides fuel and mixed catch statistics per gear type and size category. These where combined into a mixed fuel consumption ration for each segment, see table 1.

Table 10. Fuel use per gear class JRC (2010)

Swedish Fishery 2008 (JRC)		Demersal trawlers and/or demersal seiners 0m-10m	Demersal trawlers and/or demersal seiners 10m-12m	Demersal trawlers and/or demersal seiners 12m-18m	Demersal trawlers and/or demersal seiners 18m-24m	Demersal trawlers and/or demersal seiners 24m-40m	Pelagic trawlers over 40m	Pelagic trawlers 24m-40m
Capacity	Number of vessels	14	50	108	54	32	11	24
	Fleet GT (1000)	0.07	0.65	4	5.51	6.98	7.33	7.82
	Fleet Kw (1000)	1.16	8.8	26.5	20.5	21.3	21.8	22.5
Employment	Engaged crew	22	67	205	179	125	99	144
Effort	Days at sea (1000)	0.6	3.0	9.9	5.7	3.9	2.3	3.1
	Fishing days (1000)	0.6	3.1	9.9	5.9	3.8	2.0	2.9
	Energy consumption (1000 Liters)	184	775	6439	7144	5482	8299	9416
Landings	Live weight of landings (1000t)	0.054	1.122	10.276	13.359	9.272	88.692	82.757
Mixed fuel consumption		3.412	0.690	0.627	0.535	0.591	0.094	0.114
Cod catch	*1000t*	0	0.131	1.381	3.333	2.838	0.000	0.276
Herring catch	*1000t*	0.017	0.42	2.505	4.275	1.103	43.504	38.194

5.1.2. Fuel use per stock (cod trawlers)

The two cod fisheries where found to be similar in fleet structure and most boats had quotas and landings in both areas: logbook data confirms that gear code ratio (312 resp. 319) and mesh sizes are very similar and average vessel length only 5% longer with 14% larger engine effect installed in the western area, see table 4.

However they were differed in terms of catch per unit effort – in the western area it took 31% longer time to catch the same yield as in the eastern – even though the average vessels were slightly bigger and with larger engine size.

Thus, to distinguish fuel performance between stocks were only average national data are available, we assumed the fuel per catch µ to be proportional the effort **E** used to catch a landing **L** and a fleet specific efficiency constant **c**, see equation 3.

Equation 3:

$$= \alpha(\frac{E}{L} * c)$$

Table 11. Technical difference between Swedish cod trawlers in the Baltic Sea

ICES subdiv.	Total landing	Cod	Avr. kW	Avr.Effort (h)	Avr. Mesh size (mm)	Avr. month	Average Length
22	315	280	184	2	110.0		
23	7 511	6 458	295	125	107.1	3.5	15.8
24	1 303 717	1 250 067	492	6409	109.9	7.9	22.4
25	5 887 075	5 774 653	428	22109	110.0	6.1	21.3
26	2 050	1 950	596	20	110.0	1.7	32.5
27	49	49	115	14	110.0	9.0	10.5
30	780	780	270	24	110.0	8.3	13.6

By this we assume the specific efficiency constant c to be similar which enables equation 2 to be formulated as a quota of fuel consumptions rates between the regions, from which the effort quota and the landing quota is known, and thus a linear relations ship between the consumption rates can be established only dependent on the catch per unit effort, se equation 2.

Equation 4:

$$\frac{\mu_E}{\mu_W} = \frac{E_E}{E_W} * \frac{L_W}{L_E} = \frac{CPUE_W}{CPUE_E} \approx 1{,}31$$

By this the average species specific fuel consumption can be formulation as the weighted average of the two components and their specific values obtained by inserting equation X into equation Y.

Equation 5:

$$\mu_T = \frac{\mu_E * L_E + \mu_W * L_W}{L_T}$$

Thus, the stock specific fuel consumptions can be approximated as:

- Cod trawling SE Eastern stock 2008: **0.55 l/kg**
- Cod trawling SE Westerns stock 2008: **0.72 l/kg**

5.1.1. Fuel use per stock (herring trawlers)

For the herring trawlers, the boat size were large enough to separate the two fisheries directly in step 1 derived from table 5.1.1

- Herring trawling SE Eastern stock 2008: **0.15 l/kg**
- Herring trawling SE Bothnian stock 2008: **0.27 l/kg**

5.1.2. Fuel emissions

Exhaust emissions from marine diesel engines consist mainly of water vapor, carbon dioxide, carbon monoxide, oxides sulphur and nitrogen, partly reacted and non-combusted hydrocarbons and particles. Also small amounts of metals and organic micro pollutants are emitted. (Ecoinvent transport report v2.0).

The combustion emissions can be divided into emission *depended on the fuel*, and those only dependent on the *combustion process*. Carbon dioxide (CO_2) emission is mainly dependent on the type of fuel and the carbon content, which can be approximated but the density. Sulphur dioxide (SO_2) is exclusively dependent on the fuel sulphur content.

In Jungbluth (2003) a “S-content of 3.5 M% for marine bunkers is reported, resulting in an emission index of 70 g/kg SO_2. The CO_2 emission index is determined as 3080 g/kg, assuming a C-content of 84 M%” The Swedish fishing fleet refuels not only in Sweden, but in all other Baltic countries were fish is landed, however the largest concentration of fishing boats is in the Gothenburg region.

Two suppliers (Donsö bunkringsservice Ragnar Kristensson, contacted 2010-12-14 and Börjesson Olja Öckerö, contacted 2010-12-14) are regarded as large suppliers in the region. Both state that today all fishing boats are using the same product “Gasoil”, “E10”, “Eldningsolja” from the suppliers Shell (newly bought by ST-one), Statoil or Preem.

5.2. Coolants

In the Nordic countries, cooling systems on board larger ships have more or less followed the inferential laws which first outfaced CFC-12 coolant with extreme ODP and GWP values in 1994 by the Montreal convention, to be replaced with HCFC-22 (also called R-22).

In 2000 the outfacing of R22 began in EU towards coolants with null ozone depletion potential, generally to the type HCF for smaller system or ammonia (NH3) for larger systems. Sweden still allows usage but not installation or refilling of R22 systems. See table 12.

Table 12 – Cooling agents used in Nordic fisheries including global warming potential (GWP) and ozone depletion potential values (ODP) provided by Naturskyddsverket

Commercial name	Category	ODP	GWP	Remark
R12	CFC	1	8500	Banned 1994, not allowed to be used
R22	HCFC	0.055	1700	Banned 200, not allowed to be refilled or installed
HFC mix retrofit (417A, 422A+B, 427A	HFC	0	2000	Typical Nordic retrofit mix
R134a	HFC	0	1300	*only smaller systems
R404a	HFC	0	3260	*only smaller systems
R507	HFC	0	3800	
Ammonia (NH3)	other	0	0	*only larger systems
Approximated general CFC in Sweden (this study)	HFC	0	2000	

http://www.naturvardsverket.se/sv/Start/Produkter-och-avfall/Ozonnedbrytande-amnen/Koldmedieforteckning/

For coolants we used the rate of similar Norwegian boats (Pelagic: 0.02g/kg catch; Demersal: 0.22g/kg catch) (Winther et al. 2009). However the mixtures was modified since coolants of R22 is basically phased out in Sweden today and replaced by H*FC's* or ammonia for all except two pelagic vessels (Sander 2011).

An approximation from a recommended cooling systems technician on west coast (also serving Baltic vessels) suggest that 70% of all types of vessels he's serving uses ammonia systems and otherwise the most commonly used systems are R134(CFC) or R507 (Gjertz 2012). However R22 systems still exist. Commonly all boats above 15m uses a cooling room for the fish on ice and ice production which typically is produced at dock with electricity from shore. In case of pelagic fishery the fish are stored in RSV tanks.

Based on above stated information we assumed and modeled:

The same coolants emissions rate as shown in the Norwegian study (Pelagic: 0.02g/kg catch (RSV tanks); Demersal: 0.22g/kg catch (Cooling room + Ice*))

The mixture of coolants was set to 70% ammonia and 30% general CFC with GWP 2000 and productions lifecycle approximated with R22 (the only coolants in Ecoinvent database)

5.3. Antifouling

Antifouling agents are bottom paint used on maritime vessels to avoid biogenetic growth, which by definition are toxic to at least some organism in the ecosystem. 2001 an LCA survey was conducted in Sweden that quantified the quantity per catch and representative brand Jotund commonly used (Ziegler 2002). This has the property of 26% cupper(I)oxide (an active substance also important in the characterization of marine ecotoxicology).

For antifouling we used data from a previous Swedish cod *LCA* (Ziegler 2002) but with leakage rates from a Danish study comparing both cod and herring fisheries from 2004 (0.12ml/kg cod; 0.024ml/kg) herring) (Thrane 2004).

This was combined with background data from an Eco invent LCA model of white alkyd paint (white, 60% in solvent, at plant, European production) (Ecoinvent 2007) , where the known properties of the Jotund productions were inserted. This included copper production; a matched energy input (14.7 MJ) and reduced sea transport distance (1035km UK-Norway).

5.4. Capital goods

Capital goods. i.e. construction of the infrastructure used, applies in this case mainly to the production of the fishing boat, which is a question of depreciation, i.e. how many years are we estimating the vessel to fish and how much is it going produce during this time period.

The Swedish board of fisheries calculated the average age to 31years (boats over 12m) in 1999, and thus a minimum limit. Our theoretical lifespan is conservatively set to 40years, 33% higher than the average lifespan, and less than the doubled lifespan based on the recent years subsidy's for scraping old vessels (Fiskeriverket 2010).

Capital goods usually ends up when a minor contribution (at least when if only regarding climate change) and can be modeled a little bit more roughly or sometimes excluded. Therefore, we approximated the fishing vessels with a barge tanker(1500 DWT) of which a complete LCA is available (Ecoinvent 2007), but scaled down the load according to dead weight tonnes, which were available from the Swedish logbook. Since this is a minor flow below the cut off criteria and both vessels are more or less made out of steel, such a approximations could be motivated, se equation 6 and input table 13.

Equation 6:

P= DWT barge tanker/ DWT fishing boat* 1/ (amount of years fishing * annual catch)

.

Table 13. Input parameters for capital goods calculation

	Pelagic	Demersal
DWT	500	100
T	40 years	40 years
Annual catch (kg)	6 230 906	281 952

5.5. Nets

All studied fisheries are trawl dominated (pelagic or demersal) and we assumed no greater difference in gear used per kg catch, thus again using previous cod study to represent both fisheries (1g trawl (LDPE + Iron)/kg catch) (Ziegler 2002).

5.6. Other background data

Background system data flows was acquired from literature and modeled with the Ecoinvent LC database v2.0 (Ecoinvent 2007).

5.6.1. Ice production & Plastic boxes

Ice production and plastic boxes are the same as used in Danish fisheries from 2004 (0,75 kg ice, 3g HDPE per kg landed fish) (Thrane 2004), produced on shore using Swedish electricity mix. Leakage is assumed to be negligible leakage due stationary rig.

5.6.2. Engine lubricant

Engine lubricant was based on a Spanish mackerel *LCA* assuming the same average relationship between fuel and lubricant oil (0.025%) (Ramos et al. 2011)

6. Benchmarking

The main results of this case study were grouped into single stock overfishing, ecosystem impacts and standard LCA impact categories (fuel dependent emissions). All results are plotted relative the highest contributor in each impact category (Fig 6).

6.1. Benchmarking 2008

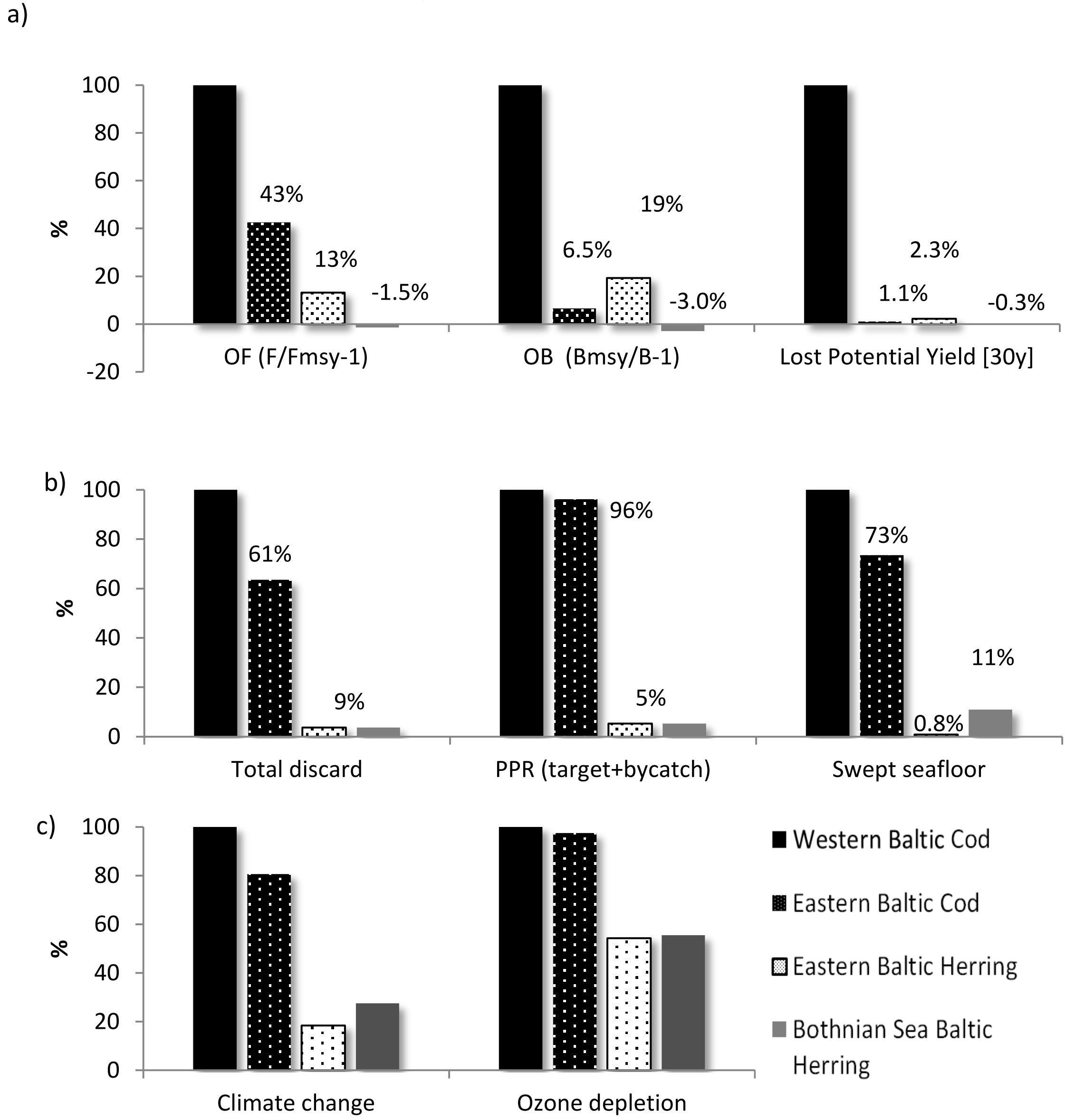


Fig. 6. Relative benchmarking comparing Swedish trawlers targeting Eastern cod, Western cod, Eastern herring and Bothnian herring in 2008. All impacts from the four fisheries are plotted relative the highest contributor in each impact category. Impact categories are grouped as a) target stock, b) ecosystem and c) emissions.

Benchmarking results in terms of absolute potential impacts is shown in table 14, where the ranking in each impact category are marked in decling shades of grey, with the largest impact marked in darkest grey.

Table 14. Absolute benchmarking 2008, comparing potential impacts per kg edible yield, for Eastern and Western Cod and Eastern and Bothnian herring. All potential impacts from the four cod stocks are ranked from highest (dark grey shade), by a gradient of coloring to the lowest (no shade). Impact categories are grouped as a) target stock, b) ecosystem and c) emission, and by priority group; high, medium, low and very low.

Impact category	*Unit*	**Western Cod** (22-24)	**Eastern Cod** (25-32)	**Eastern Herring** (25-32-gov)	**Northern Herring** (30)
a) Target stock					
Overfishing by Fishing mortality (F/Fmsy-1)	kg F_{MSY} eq.	**46.4**	**19.7**	**6.1**	**-0.68**
Overfishedness of Biomass (Bmsy/B-1)	kg B_{MSY} -eq.	**6.0**	**0.4**	**1.2**	**-0.18**
Lost Potential Yield (30years)	kg LPY	**34.0**	**0.4**	**0.8**	**-0.11**
b) Ecosystem					
Total discard	kg	**0.43**	**0.26**	**0.04**	
PPR (incl. target catch)	kg C	**8.4E+02**	**7.9E+02**	**4.1E+01**	
Seafloor area swept	m^2	**1.0E+04**	**7.6E+03**	**3.5E+01**	**1.1E+02**
c) Emissions					
Climate change	kg CO_2 eq.	**6.1**	4.8	*1.2*	1.8
Other (17) impact categories of lower priority groups	*multiple*	**17/17**	**16/17**	**17**	**16/17**

6.1.1. Target stock

In absolute numbers, the LPY value reached 34 kg potentially lost yield per each kg edible yield for Western cod, and it greatly exceeded the other stocks (Table 3). The Eastern herring stock actually exceeded the Eastern cod stock in terms of LPY while the Bothnian herring in fact had a negative lost yield (-0.11 kg per kg edible yield).

The main drivers of LPY can be seen in the OF and OB scores, for example explaining the negative results for Bothnian herring by negative values of OB and OF, i.e. this stock was both larger than B_{MSY} and exploited below F_{MSY} in 2008. The eastern cod actually had lower value of the fishing mortality based OF than Eastern herring, yet the remarkable recovery of cod biomass (see 3.2) and decrease of herring biomass resulted in higher OB scores for the eastern herring, which ultimately led to higher LPY scores, positioning the herring in 2008 in worse stock status than eastern cod.

6.1.2. Ecosystem

In terms of total discards, the statistical differences between stocks can be questioned, see discussion 4.1.2, but the available data suggested highest total discard in the Western cod stock and at least one order of magnitude better than the herring stocks. If the cod stocks are pooled and regarded as one common bycatch rate (19%) it is still considerably higher than the average global discard rate of 8%, the average demersal finfish rate of 9.5% or average north East Atlantic fisheries 13% (FAO 2005).

The composition of discards were evaluated by VEC methodology, but instead of providing an stock specific absolute number, only the species composition was examined (see supplementary information) and found to be mainly composed of juvenile cod (approximate 70%) in both cod fisheries which are classified as Vulnerable on the IUCN Red List.

In terms of PPR, the differences between cod and herring increases drastically in favor of the herring (Fig 3), mainly based on the trophic level difference of target stocks, but also approximations of bycatch, and thus the joint need of primary production required, here measured in sequestrated carbon.

Swept seafloor was highest for the codfisheries, while the herring fisheries were only by a smaler fraction fished demersally (10%), yet the diffreces within the same species groups are direcly realted to the catch per unit effort data, suggesting that the Bothian herring requires larger sweep than Eastern herring, exceeed by both Eastern and Western cod (largest sweep).

6.1.3. Fuel dependent impacts

Highest GHG emissions per the edible products were again found in the Western Baltic cod fishery (6.1 kg CO_2eq) compared with 4.8 kg for the Eastern cod, 1.2 kg for the Eastern herring and 1.8 kg per kg edible filet for the Bothnian herring fishery, respectively.

Compared with Norwegian cod and herring fisheries these emissions are relatively high, based on the fuel consumption per round weight as the best comparable parameter across the different scope of studies, which suggests that Swedish cod fisheries had 2.3 times higher fuel dependent emission and herring fisheries had1.6 times higher (Winther et al. 2009).

All other standard impact categories included in the ReCiPe bundle resulted in a similar ranking pattern driven by the fuel consumption however slightly different in the case of ozone layer depletions, see figure 7

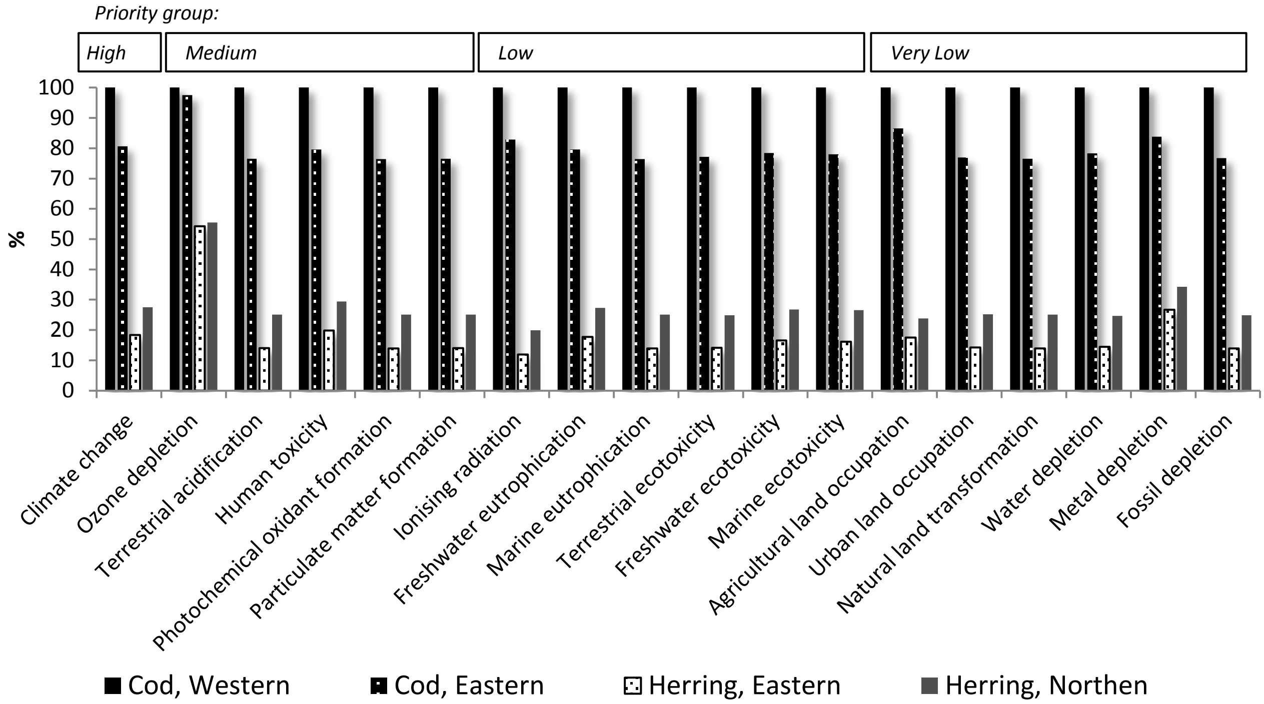


Figure 7. Relative benchmarking comparing Eastern Baltic Cod (25-32), Western Baltic Cod (22-24), Eastern Baltic herring (25-32-gov) and Bothnian herring (30). All impacts from the four cod stocks are normed against the highest contributor in each impact category. Impact categories are grouped as a) target stock, b) ecosystem and c) emission.

6.2. Temporal and spatial considerations

Overfishing in terms of LPY showed a declining trend for both cod stocks during the time period from 2002 to 2008, which was also continued for the following two years (Fig. 8).

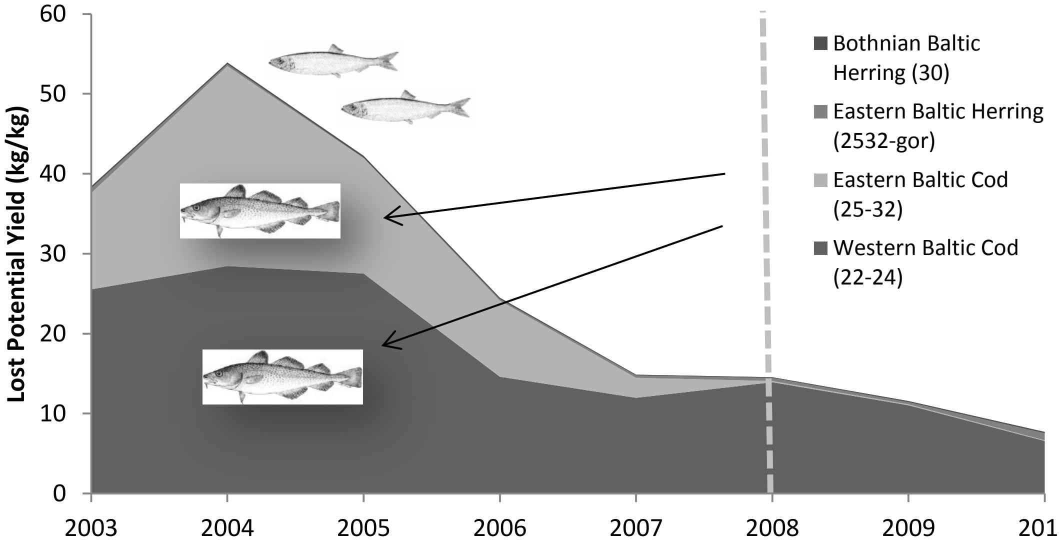


Fig. 8 Lost Potential Yields between 2003 and 2010 (two years extended beyond scope of the main analysis, see separating dotted grey line), regarding Eastern Baltic cod (light grey), Western Baltic Cod (dark grey), as well as Eastern Baltic herring and Bothnian Baltic herring (minimal contributions).

For the two larger stocks; Eastern cod and herring, the development of fuel consumption over time indicates a similar pattern as the B_{MSY}/B (i.e. the OB category without -1 term for best fit).

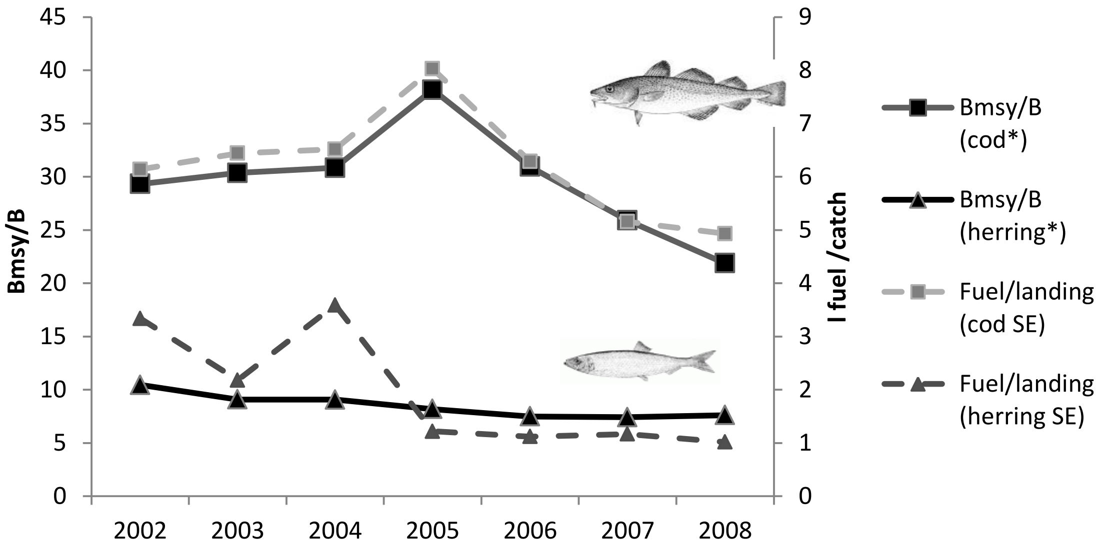
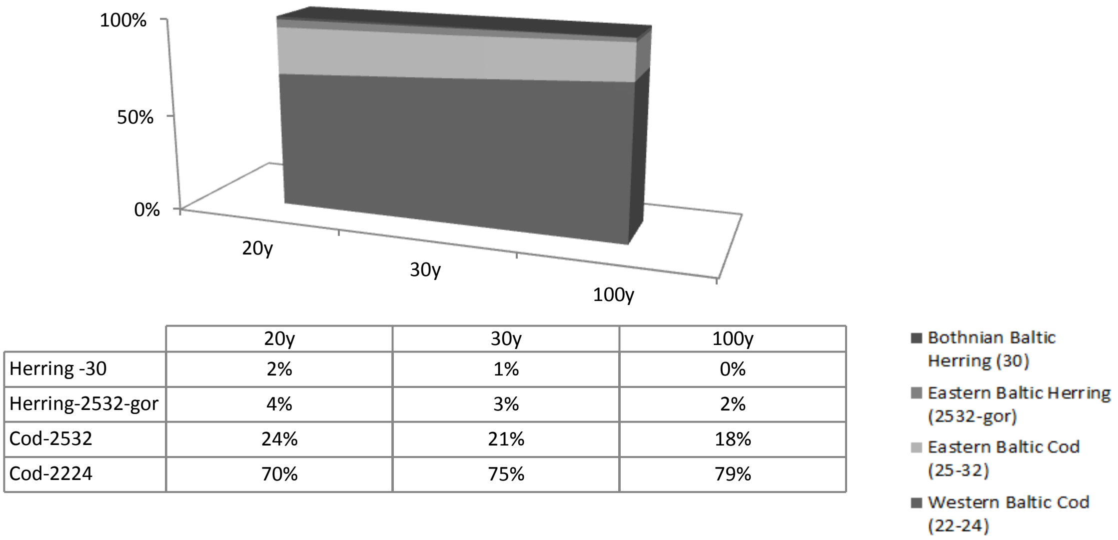


Figure 9. Fuel use and overfishedness indicator (B_{MSY}/B) in Swedish fisheries for cod and herring fishery in the Eastern Baltic. Fish illustrations: FAO.

Fuel prices have risen during this period but fuel consumption correlates better with OB for the cod fisheries, se figure 9, i.e. the key driver for all impact categories in the emission group, following a declining, and thus improving pattern as the biomass increases.

6.3. Sensitivity analysis

(I) Lost Potential Yield [choice of characterization model] When the timperspective T was altered, the aboslute values increase for all stocks, but values for the overexploitet stocks increased at a higher rate, however the ranking remaind robust, see figure 10.



	20y	30y	100y
Herring -30	2%	1%	0%
Herring-2532-gor	4%	3%	2%
Cod-2532	24%	21%	18%
Cod-2224	70%	75%	79%

Fig. 10 Sensitivity of Lost Potential Yield (LPY) results, due to alternative time perspectives / iteration number T.

When the projection model for lost potential yield was compared with a simpler MSY/L-1 model, the Western Baltic cod turned out as a better alternative than the Eastern, even though the common opinion, the OB and the OF categories dictate otherwise. This is due to the missing the long term perspective, thus falsly being benefitted by the high F vaules while the Eastern stock are in a state of recovery. Thus, the LPY scores are better indicator and the influece of choosen T value does not alter the main conclusions.

(II) Allocation of mixed catch on fishing boat [mass / economic] As an alternative to mass allocation in the subdivision of environmental flows originating on the fishing boats, we tried to separate burdens based on the relative economic value.

Since the cod landings were extremely clean (97% cod in mass), the impact switching from mass to value was small (3%). For herring, on the other hand, the landings only consist of 37% herring, the rest being sprat that attains only half the value of herring.

In this case, basing the distribution of impacts on the economic value would increase the burdens of herring by around 50%, but it would not change the overall conclusions of the study regarding comparisons between stocks and development over time.

(III) Missing post-landing chain Previous studies have shown the fishing stage of the product LCA to be most influential, however post landing chains could be very diverse (hard to assume on general basis), but important if waste flows occur.

For example any waste or loss in the production chain would generate an increase in all types of impact that can be measured in terms of trawled area, overfishing or carbon dioxide equivalents stressing the importance of ensuring that fish and seafood products are actually are consumed and not wasted.

For seafood, this figure has been estimated to be 7% avoidable (edible) food waste (WRAP 2008). Applying this rate to landings from the Western Baltic cod fishery gives a net increase of approximately 150 m^2 swept trawl area, 1.4 kg overfished B_{MSY}-equivalents and 350g CO_2 equivalents per edible kg consumed.

(IV) By products used [mass /economic] Despite the fact that the post-landing supply chain was excluded from the study, we did choose the comparisons unit as one kilogram of edible fish landed, for comparability and to reflect the function of supplying protein for human nutrition. This means, however, that we need to take a decision on whether or not the non-edible parts of the fish should carry a part of the burden.

Since the processing stage was not included and we had no information on to what extent and how herring and cod by-products were used, we chose to place all burden on the edible parts, as a worst case. Had we instead assumed full utilization of by-products and placed the burdens on them in relation to their mass, all fisheries would have has considerably lower impacts and this would have favored cod compared to herring as cod has a lower edible yield.

Use of by-products would decrease the differences found between herring and cod fisheries, while going from mass to value, as the basis for separation would strengthen them.

7. Discussion

This study represents the first Life Cycle Assessment application on seafood with a quantitative impact assessment including target stock besides the traditional emission based categories, and by this arguably the first seafood LCA in line with the methodology, which should capture all relevant environmental aspects (ISO 2006b; ILCD 2010). This case study conveys some of the most relevant aspects for unbiased comparison of these four fisheries relative each other in terms of food production for human consumption.

However, LCA is a multidisciplinary tool to distinguish between large and small potential impacts, and it is important to note the complementary role of LCA in relation to risk-based single stock-, multispecies- and ecosystem approaches, used for example for setting fishing quotas. However, in future LCA studies other aspects could be considered, such as multispecies interactions, size and age distributions or local habitat sensitivity to trawling or bycatch composition.

The results from this work clearly showed that the novel methodology could be used to benchmark environmental performance of fisheries at midpoint level. We also showed that the stock is the preferable unit and spatial resolution, rather than just choosing the right species, and the year of assessment is likewise important, just like in fisheries management. Moreover the temporal variation makes sustainability assessments of seafood quickly outdated if not updated continuously. However, a certain lag in data availability will always be an issue to consider, especially in published press, but future applications in the seafood industry could be based on more updated input data or even future projections provided by separate stock assessment models.

7.1. Seafood benchmarking by LCA

The benchmarking scores should primarily be interpreted relative each other, from which we conclude that the Western cod in 2008 performed worst in all included impact categories, followed by Eastern cod which ranked second worst in 21 out of 24 impact categories.

The Eastern herring fishery had the best fuel performance, thus ranked best in all emission impact categories (16), while the Bothnian herring excelled in single stock status relative the Maximum Sustainable Yield framework, indicating a buffer for future exploitation with the negative LPY score.

7.1.1. Target stock

Direct potential impact on target stock, expressed as the lost potential yield index, indicates that Western cod has the most severe degree of overfishing, driven by both small spawning stock biomass (the OB impact category assessing the distance towards B_{MSY}) and too high fishing mortality (the OF impact category measuring the distance towards F_{MSY}). The OF should here be recognized as the most robust impact category of the three provided impact categories, based on the fishing mortality alone which aggregates landings with discards of juveniles and assessments of underreports and illegal landings (Emanuelsson et al. submitted 2013).

Eastern and Western cod stocks are good examples where the last two decades of regimes shift has been considered cod hostile in terms of reduced spawning success, yet the Eastern stock has rapidly recovered when fishing mortality dropped. This is a trend which has continued also after the time period included in this study (Cardinale and Svedang 2011). Thus, even though many ecologically complex mechanisms influence the fish stocks, the impact categories tested here captures the main drivers.

The target stock group of impact categories are considered as highly important, motivated by the large national public debate of overfishing in fisheries management and seafood certification in the Baltic sea region (Lövin 2007; KRAV 2013), as well as the international focus on single stock exploitation (FAO 2012), and the more specific goal of European fishery management (EC 2006) .

7.1.2. Ecosystem

High resolution discard data is cornerstone in the available ecosystem describing impact categories (PPR, VEC), but retrieving them sub-dived into national fleet (stock) specific data proved a challenge even when national discards program existed. Hence we only assessed TD as a demonstration in line with the exploratory scope of this study, and even that could be questioned based on the lack of data point in the western stock. Other fisheries could of course have more data available, but another option could be to skip the national fishery specific resolution, or even in worst case only apply the FAO standard rates (FAO 2005).

Occurrence of threatened fish species according to the Red List (VEC) has been suggested to differentiate the impacts attributed from the species composition of discards {Hornborg S, 2013 #668}. In this study, this metric was excluded after analysis of the species list, mainly due to lower fish diversity in the brackish Baltic Sea and the fact that the greatest amount of threatened species discarded was in fact the targeted cod itself, which should be noted, although the Red List in this case aggregates the all four cod stocks managed around the Swedish coastline, including the depleted Skagerrak stock, whereas the LPY OB and OF here are far more accurate descriptors of potential target stock impact.

However, despite this extreme situation, we stress the importance of checking for threatened species as defined by the Red List (categories Vulnerable, Endangered, or Critically Endangered) in the discards, see section 4.2.

Then the primary production required (PPR) to produce both landing and discard was taken into account, the differences between cod and herring fisheries were amplified; due to the higher food web position for cod. However, the potentials and limitations of using primary production flows as resource use from different landings and discards is currently debated (Parker and Tyedmers 2012; Hornborg et al. 2012), and can perhaps be even more questioned in a highly eutrophicated area as the Baltic Sea.

The swept seafloor area by cod trawling are higher than a previous assessment regarding Swedish cod fisheries conducted in 1999 (Ziegler 2006), mainly because of updated measurement of speed and effective gear width in this study. Yet, if the same technical baseline is assumed, the corresponding area has decreased since 1999 with 45-55% in line with the improved stock situation and increased catch per unit effort. However, further methodological developments that incorporate sensibility would be needed, to fully utilize the possibilities of swept area as biodiversity indicator.

7.1.3. Fuel dependent impacts

The emission and abiotic resource categories displayed a similar pattern of ranking between the four stocks, highly correlated to the fuel consumption for all impact categories, since the use of nets, ice boxes, vessel production and as well as harbour services are less important than the fuel combustion and fuel production processes.

However, the fuel data in derived from the JRC report is considered to be too intransperent for a proper correlation analysis in this dataset. Herring fuel consumption between 2002 and 2004 are considered not robust in the sourcing data material (JRC 2010).

Other non-fuel related emissions, such as from antifouling and leakage of coolants affects several of the toxicity impact categories. However, the maximum values are yet half of the contributions from combustion in each category, suggesting that the magnitude of flows is small based on the literature values used, which again stresses the importance of fuel consumption.

The present case study also demonstrates that the stock-fuel relationship is not a reliable two-way mechanism, and problematic in terms of fuel data availability from a top down modeling approach. The stock in the best condition was the Bothnian herring, fished by smaller boats than those targeting Eastern herring. Nevertheless, in terms of fuel efficiency, the larger boats in the Eastern herring fishery were superior. In any case, future seafood LCA should aim at including the best available stock status and fuel consumption data to further enlighten the relationship and complexity of the tradeoffs in between, not rely on only one of the parameters to determine the other.

However, for the Eastern cod fishery, the main change over time has been the stock status, while the gear used and management system have been rather stable, which excludes that the decrease would be caused by something else than a ‘stock effect’. A similar conclusion about increasing fuel efficiency over time was drawn in a study using the same aggregated dataset for fuel use, but taking a rather different approach on how to divide the fleet fuel use to individual fisheries, therefore arriving at different absolute numbers but the same trends {Ziegler, Submitted manuscript. #669}

7.2. Future outlook

The multiple dimensions a midpoint based LCA provides makes the interpretation of the score card more complex than what could be assumed understandable for an ordinary consumer, although it could be facilitated by grouping techniques and expert panels. Thus the application is more likely to be found within fisheries management, seafood labels or industrial experts. Future work could however focus on providing more easily interpreted single score indices, i.e. endpoint characterization adopted specifically for seafood productions systems.

Many of the factors responsible for the total benchmarking score are influenced by management regulations, such as when, where and how much to fish. This drives the target stock categories, while technological regulations and subsidies influence many of the emissions based impact categories. Fisheries management could therefore make use of LCA results to incorporate broader and more complete set of environmental threats, thereby avoiding optimizing regulations with regard to one aspect, while sub-optimizing with regard to others without being aware of the trade-offs (Hornborg et al. 2012).

If the resolution was increased and individual fishing boats are benchmarked rather than whole fleets, optimization and skill sharing among skippers could be facilitated on a vessel or skipper level to improve fuel/catch ratio, gear selectivity, seafloor impacts even further.

8. Conclusion

- The present a case study represents the first application in Life Cycle Assessment where new biological impact categories, covering potential impact of single stock overfishing, discards and swept seafloor are used along with traditional emission based impact categories.

- The study demonstrates how management, fishing industry and eco-labeling organizations could use LCA supported benchmarking to compare and convey quantitative information of environmental performance.

- The Western Baltic cod fishery was shown to have the highest impact in all categories, although Eastern Baltic cod and herring, as well as Bothnian Baltic herring showed much more complex ranking between different impact categories.

- Time series of lost potential yields visualized the improvement of Eastern Baltic cod and a robust ranking amongst fisheries in terms of single stock overfishing related to the maximum sustainable yield framework.

- Ecosystem impacts were assessed in terms of swept area, discards and primary production required, although data availability restricted the quantitative comparisons in terms of Red Listed species in the discards.

- Fuel use on the fishing vessel was the main driver behind all traditional LCA impact categories, but fuel consumption alone was shown to be a weak indicator of stock status between different stocks, as many other factors influence the fuel use of a fishery.

- Applying the new biological impact categories, benchmarking through LCAs is concluded to be a useful complementary tool for fisheries managers, the seafood industry and seafood certification initiatives, and indirectly also for consumers

9. Acknowledgements

We kindly thank Yvonne Walther for assistance with discard data, Mikael Thörn for practical work regarding trawl surveys and Per Nilsson and Daniel Valentinsson who have been valuable discussion partners as well as Staffan Larsson at STPO, the Swedish Cod Fishermen's Producer organization.

The work was funded by the European Commission (LC-IMPACT FP7 Grant Agreement 243827) and the Swedish Research Council.

10. References

Baden, S., Emanuelsson, A., Pihl, L., Svensson, C.J. & Åberg, P. (2012) Shift in seagrass food web structure over decades is linked to overfishing. *Marine Ecology Progress Series* **451**:61-73.

Cassini, M., Hjelm, .J, Molinero, J-C., Lövgren, J., Cardinale, M., Bartolino, V., Belgrano, A. & Kornilovs, G. (2009) Trophic cascades promote threshold-like shifts in pelagic marine ecosystems. *Proceedings of the National Academy of Sciences* **106**:197-202.

Estes, J.A., Terborgh, J., Brashares, J.S., Power, M.E., Berger, J., Bond, W.J., *et al*. (2011) Trophic Downgrading of Planet Earth. *Science* **333**:301-306.

Frank, K.T., Petrie, B. & Shackell, N.L. (2007) The ups and downs of trophic control in continental shelf ecosystems. *Trends in Ecology & Evolution* **22**:236-242.

Hornborg, S., Nilsson, P., Valentinsson, D. & Ziegler, F. (2012) Integrated environmental assessment of fisheries management: Swedish *Nephrops* trawl fisheries evaluated using a life cycle approach. *Marine Policy* **36**:1193-1201.

Hornborg, S., Belgrano, A., Bartolino, V., Valentinsson, D. & Ziegler, F. (in press) Trophic indicators in fisheries: a call for re-evaluation

Hornborg, S., Svensson, M., Nilsson, P. & Ziegler, F. (in prep 1) The IUCN Red List Categories as a framework for communication regarding discard impacts in fisheries

Hutchings, J. (2000) Collapse and recovery of marine fishes. *Nature* **406**:882-885.

Reynolds, J.D., Dulvy, N.K., Goodwin, N.B. & Hutchings, J.A. (2005) Biology of extinction risk in marine fishes. *Proceedings of the Royal Society B: Biological Sciences* **272**:2337-2344.

Cardinale M, Svedang H (2011) The beauty of simplicity in science: Baltic cod stock improves rapidly in a 'cod hostile' ecosystem state. Marine Ecology-Progress Series 425:297-301. doi:10.3354/meps09098

EC (2003) COM 302 Integrated product policy - building on environmental life-cycle thinking. Comisssion of the European Communities, Brussels

EC (2006) COM 360 Implementing sustainability in EU fisheries through maximum sustainable yield. Communication from the Commission to the Council and the European Parliament. Brussels

Ecoinvent (2007) Ecoinvent v2.0 reports No. 1-25. Swiss Centre for Life Cycle Inventories (LCA database - buy accesss at www.ecoinvent.org), Duebendorf, Switzerland.

Emanuelsson A, Sonesson U, Pihl L, Sköld M, Ziegler F (submited 2013) Overfishing, Overfishedness and Wasted Potential Yield: new impact categories for biotic resources in LCA (trans: Productions SF). First edn., Gothenburg

Emanuelsson A, Ziegler F, Hornborg S, Sonesson U (2013) LC-IMPACT Deliverable 4.2 LCA case study – fisheries: Benchmarking Swedish cod and herring products by spatial-temporal Life Cycle Assessment.

Emanuelsson A, Ziegler F, Pihl L, Sköld M, Sonesson U (submitted 2013) Accounting for Overfishing in Life Cycle Assessment: new impact categories for biotic resource use. The International Journal of Life Cycle Assessment

FAO (2005) Discards in world's marine fisheries, un update. Fisheries Technical Paper. Rome

FAO (2012) The state of world fisheries and aquaculture. United Nations Food and Agriculture Organization, Rome

Fiskeriverket (2010) Fiskarkårens struktur samt fiskeflottans storlek och sammansättning 1999 - Statistik över antal yrkesfiskare och fiskefartyg i den svenska fiskeflottan den 31 december 1999. The Sedish Board of Fisheries, Gothenburg

Froese R, Pauly D (2011) FishBase 2000: concepts, design and data sources. http://www.fishbase.de.

Gjertz P (2012) Technican at Hälsö Kyl & Värme. Information about cooling systems in Swedish Fisheries edn., Hälsö

Goedkoop M, Heijungs R, Huijbregts M, Schryver A, Struijs J, Zelm R (2009) ReCiPe 2008 - A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Haag

Gutiérrez NL, Valencia SR, Branch TA, Agnew DJ, Baum JK, Bianchi PL, Cornejo-Donoso J, Costello C, Defeo O, Essington TE, Hilborn R, Hoggarth DD, Larsen AE, Ninnes C, Sainsbury K, Selden RL, Sistla S, Smith ADM, Stern-Pirlot A, Teck SJ, Thorson JT, Williams NE (2012) Eco-label conveys reliable information on fish stock health to seafood consumers. PLoS One 7 (8):e43765. doi:10.1371/journal.pone.0043765

Hornborg S, Nilsson P, Valentinsson D, Ziegler F (2012) Integrated environmental assessment of fisheries management: Swedish Nephrops trawl fisheries evaluated using a life cycle approach. Marine Policy 36 (6):1193-1201. doi:10.1016/j.marpol.2012.02.017

ICES (2009) Report of the ICES Advisory Committee 2010 - Book 8: Baltic Sea. ICES Advice. Copenhagen

ICES (2011) Report of the Baltic Fisheries Assessment Working Group (WGBFAS) : ANNEX: WGBFAS_Cod in 25-32. Copenhagen

ILCD (2010) ILCD Handbook - General guide to life cycle assessments - Detailed guidance. First edition edn. Joint Research Centre of the European Commission, Luxenburg

ISO (2006a) ISO14040 Environmental management - Life cycle assessment - Principals and framework. International Organization for Standardization, Geneva, Switzerland

ISO (2006b) ISO14044 Environmental management - Life cycle assessment - Requirements and guidelines. International Organization for Standardization, Geneva, Switzerland

JRC (2010) The 2010 Annual Economic Report on the European Fishing Fleet. JRC Scientific and Technical Reports. Ispra, Italy

JRC (2011) 2003 - 2009 Dataset from Annual Economic Report on the European Fishing Fleet. JRC Scientific and Technical Reports. Jordi Gullien, Ispra, Italy

KRAV (2013) KRAV ecolabel webpage. http://www.krav.se.

Livsmedelsverket (2012) The Swedish Food Database. 2012-03-01 edn., Uppsala

Lövin I (2007) Tyst hav. Ordfront Förlag,

Nilsson P, Ziegler F (2007) Spatial distribution of fishing effort in relation to seafloor habitats in the Kattegat, a GIS analysis. Aquatic Conservation: Marine and Freshwater Ecosystems 17 (4):421-440

Parker R (2012) Review of life cycle assessments research on products derived from fisheries and aquaculture: a review for Seafish as part of the collective action to adress greenhouse gas emissions in seafood. Sea Fish Industry Authority, Edinburgh,UK

Parker RWR, Tyedmers PH (2012) Uncertainty and natural variability in the ecological footprint of fisheries: A case study of reduction fisheries for meal and oil. Ecological Indicators 16 (0):76-83. doi:10.1016/j.ecolind.2011.06.015

PRé-Consultants (2011) SimaPro 7.3. PRé-Product Ecology Consultants, Netherlands

Ramos S, Vázquez-Rowe I, Artetxe I, Moreira M, Feijoo G, Zufía J (2011) Environmental assessment of the Atlantic mackerel (*Scomber scombrus*) season in the Basque country. Increasing the timeline delimitation in fishery LCA studies. The International Journal of Life Cycle Assessment 16 (7):599-610. doi:10.1007/s11367-011-0304-8

Sander TP (2011) Nordiske indsatser for R-22 i køleanlæg på skibe. TemaNord København

SNBF (2010) Anonomysed logbook dataset of Swedish fisheries 2008 (not publicly available). Gothenburg

Stapenhurst T (2012) The Benchmarking Book. Taylor & Francis, Oxford, UK

Stokstad E (2011) Sustainability Seafood Eco-Label Grapples With Challenge of Proving Its Impact. Science 334 (6057):746-746

Thrane M (2004) Environmental impacts from Danish fish products. PhD dissertation, Aalborg University, Denmark, Aalborg

Thrane M, Ziegler F, Sonesson U (2009) Eco-labelling of wild-caught seafood products. Journal of Cleaner Production 17 (3):416-423. doi:10.1016/j.jclepro.2008.08.007

Thörn M (2012) Trålgeometri för Svenskt Bottentrålfiske - Datarapport från tillämpningskurs. Gothenburg University, Gothenburg

Tyedmers PH, Watson R, Pauly D (2005) Fueling Global Fishing Fleets. AMBIO: A Journal of the Human Environment 34 (8):635-638

Walther Y (1995) Bycatches of cod in Swedish trawl fishery for plagic species in the Baltic Sea. Swedish Board of Fisheries "Fiskeriverket", Gothenburg

Vázquez-Rowe I, Hospido A, Moreira MT, Feijoo G (2012) Best practices in life cycle assessment implementation in fisheries. Improving and broadening environmental assessment for seafood production systems. Trends in Food Science and Technology 28 (2):116-131. doi:10.1016/j.tifs.2012.07.003

10.1111/j.1530-9290.2012.00485.x; Zufía, J., Arana, L., Life cycle assessment to eco-design food products: industrial cooked dish case study (2008) Journal of Cleaner Production, 16, pp. 1915-1921

Vázquez-Rowe I, Hospido A, Moreira MT, Feijoo G (in press) Best practices in life cycle assessment implementation in fisheries. Improving and broadening environmental assessment for seafood production systems. Trends in Food Science & Technology (0). doi:10.1016/j.tifs.2012.07.003

Winther U, Ziegler F, Skontorp Hognes E, Emanuelsson A, Sund V, Ellingsen H (2009) Carbon footprint and energy use of Norwegian seafood products. .

WRAP (2008) The Food We Waste. v2 edn., Banbury, UK

Ziegler F (2002) Environmental Assessment of a Swedish, frozen cod product with a life-cycle perspective. A data report. SIK report. Gothenburg

Ziegler F (2006) Environmental Life Cycle Assessment of seafood products from capture fisheries. . Göteborg University / SIK -The Swedish Institute for Food and Biotechnology., Gothenburg§

Ziegler F, Nilsson P, Mattsson B, Walther Y (2003) Life cycle assessment of frozen cod fillets including fishery-specific environmental impacts. International Journal of Life Cycle Assessment 8 (1):39-47

Ziegler F, Winther U, Hognes ES, Emanuelsson A, Sund V, Ellingsen H (2012) The carbon footprint of Norwegian seafood products on the global seafood market. Journal of Industrial Ecology. doi:10.1111/j.1530-9290.2012.00485.x

Österblom H, Hansson S, Larsson U, Hjerne O, Wulff F, Elmgren R, Folke C (2007) Human-induced Trophic Cascades and Ecological Regime Shifts in the Baltic Sea. Ecosystems 10 (6):877-889. doi:10.1007/s10021-007-9069-0

11. Supplementary information

11.1. Times series LPY methodology

cod-2224	**OB**	**OF**	**LPY**
2003	15.7	3.66	25.5
2004	15.7	3.95	28.5
2005	19.0	3.79	27.5
2006	13.3	2.42	14.6
2007	11.5	2.28	12.0
2008	**19.0**	**2.45**	**13.9**
2009	15.7	2.12	11.0
2010	15.7	1.64	6.6

cod-2532	**OB**	**OF**	**LPY**
2003	11.5	2.7	12.05
2004	11.5	4.63	25.01
2005	15.7	2.74	14.43
2006	11.5	2.24	9.52
2007	10.1	1.39	2.50
2008	**8.1**	**0.16**	**0.15**
2009	4.3	0.12	0.11
2010	3.3	-0.04	0.09

her-2532-gor	**OB**	**OF**	**LPY**
2003	4.6	0.83	0.82
2004	4.6	0.56	0.45
2005	4.0	0.41	0.29
2006	3.5	0.53	0.36
2007	3.5	0.6	0.40
2008	**3.8**	**0.71**	**0.48**
2009	3.5	0.64	0.41
2010	3.5	1.14	1.04

her-30	**OB**	**OF**	**LPY**
2003	-0.41	-0.31	*-0.21*
2004	-0.44	-0.28	*-0.18*
2005	-0.49	-0.31	*-0.21*
2006	-0.44	-0.26	*-0.17*
2007	-0.42	-0.12	*-0.08*
2008	**-0.42**	**-0.11**	***-0.07***
2009	-0.53	-0.19	*-0.12*
2010	-0.63	-0.23	*-0.15*

11.2. Terminology

Allocation: (in LCA) Subdivision of inputs or outputs of a process, for example dividing fuel consumption on a fishing boat between different species of fish in the mixed catch, either by economic value, mass or other physical properties.

Benchmarking: The process of comparing business performance (originally economic, but also extended to environmental performance) against a reference performance level, typically the average or best practice.

Biomass (B): Weight unit typically used to measure a biotic population, sometimes referring to both spawning stock biomass and total biomass

By-catch: The part of the catch which is not the Target catch (see Target catch), which could either be discarded back to the sea or landed

Carrying capacity (K): The natural population around which a biotic population oscillates without human interference and larger shifts in environmental conditions.

Characterization factors (CF): Factors derived from a function of environmental relevance, used to aggregate inventory substances into potential environmental impact.

Demersal fisheries: Fisheries targeting bottom dwelling species, for example cod.

Discard: The part of the by-catch that is thrown overboard, dead or dying, or likely to die, for example non-value species, juveniles or over-quota target species)

Fishing mortality (F): Proportion of stock harvested by fisheries each year

Functional unit (FU): The unit of comparison in LCA, reflecting a function of the product, used for non-biased comparison between alternatives, such as comparing a paper cup and ceramic cup with the function of withholding a certain amount of liquid with certain quality demands specified by its function.

Impact Assessment (LCIA): The phase of an LCA where substances are characterized into impact category results, such as greenhouse gas emissions, eutrophication or wasted potential yield.

Inventory Analysis (LCI): A catalogue of substances quantified and related to the functional unit

Life Cycle Assessment (LCA): an ISO-standardized technique for assessing the potential environmental harm associated with a product or process from cradle to grave (i.e. the life cycle of a product).

Maximum Sustainable Yield (MSY): The theoretical largest yield possible to take out from biological system over an indefinite time period.

Overfishing (Overfishing through Fishing Mortality): In the broad meaning, fishing “too much” without specified reference. Several definitions exist relating to reference values, including stock size, structure and reproduction.

Overfishedness (Overfishedness of Biomass): A constructed word to represent how much smaller the biomass state is related to a desired level.

Pelagic fisheries: Fisheries targeting species in the open water column (pelagial), for example herring, mackerel and sprat fisheries

Spawning stock biomass (SSB): Biomass of fish in a stock that has reached maturity, i.e. are reproducing.

Stock: (or Fish stock) geographically and genetically limited population of a species, e.g. North Sea haddock, Eastern Baltic cod.

System boundaries: (in LCA) a set of criteria’s defining which process to be included in the studied product system.

Wasted Potential Yield: An LCA impact category developed in this thesis, that describes the exploitation rate combined with biomass state in relation to MSY framework, in terms of mass unit of yield lost, as consequence of current fishing practice.

Yield (Y): Total annual landings from a stock