Environmental Life Cycle Assessment of Norway lobster (*Nephrops norvegicus*) caught along the Swedish west coast by creels, conventional trawls and species-selective trawls.

Friederike Ziegler,[1] SIK, the Swedish Institute for Food and Biotechnology, PO Box 5401, SE- 402 29 Göteborg, Sweden, Ph. 46 31 3355600, Fax. 46 31 823782, e-mail: fz@sik.se

Daniel Valentinsson, Swedish Board of Fisheries, Institute of Marine Research, PO Box 4, SE-453 21 Lysekil, Sweden.

[1]Corresponding author

Abstract
Three fishing methods, creeling, conventional trawling, and species-selective trawling are used to target Norway lobster (*Nephrops norvegicus*), economically the second most important species in Swedish west coast fisheries. To evaluate overall resource use and environmental impact caused by producing this seafood we followed the production chain starting from the fishery itself, through seafood auctioning, wholesaling, retailing, to the consumer using life cycle assessment (LCA) methodology. That portion of the life cycle occurring on land was assumed to be identical for Norway lobsters regardless as to how they were caught. The functional unit was 300 g of edible meat (i.e., Norway lobster tails), corresponding to one kilogram of whole, boiled Norway lobsters. Major differences were found between the fishing methods with regard to environmental impact: creeling was found to be more efficient than conventional trawling in all traditional impact categories and in the two additional fishery-related categories seafloor impact and discarding. Species-selective trawling was considerably more resource efficient than was conventional trawling due to both less discards and less landed by-catch; however, selective trawling nevertheless used more resources than creeling did. The seafloor impact of trawling was quantified using a recently developed methodology. The only deficiencies of creel fishing were poorer working environment and safety and a potentially higher risk of recruitment overfishing. However, these issues could probably be handled by technological development and fisheries regulations, and should not hamper the development of the creel fishery. Improvement options were identified and quantified for the Swedish *Nephrops* fishery. The study demonstrates how LCA can be used both to compare the environmental performance of different segments of a fishery and to evaluate the environmental consequences of introducing new technical regulations to a fishery for which LCA data are available.

Introduction

Background
The Swedish *Nephrops* fishery takes place along the western coastline of the country in the easternmost parts of the North Sea, the Skagerrak and Kattegat. Annual Swedish *Nephrops* landings have fluctuated around 1000 tonnes since the mid 1980s. In 2005, 1052 tonnes were landed. Approximately 100 trawlers, accounting for 80% of total *Nephrops* landings are active in this fishery. The Swedish creel fishery for *Nephrops* started in the mid 1980s and produced approximately 10% of the total landings until the late 1990s. Between 1999 and 2005 the number of creel fishing vessels increased by 50% to 110 and in 2005, creeling

produced approximately 20% of the total landings, mainly from the northern part of the area, the Skagerrak. The minimum landing size is 40 mm carapace length and the stocks are managed as one (i.e., for the Skagerrak/Kattegat and both fishing methods). The exploitation level of the Skagerrak/Kattegat *Nephrops* stock is currently considered to be sustainable, but it is not recommended that catches should increase due to uncertainty about the stock status in relation to threshold values (Ask and Westerberg 2006). A typical *Nephrops* creel is depicted in Fig.1a. These are baited with salted herring to attract the target species. Trawls in this fishery are either single otter trawls like that depicted in Fig.1b or twin trawls, i.e., two trawls pulled in parallel. Since 2004, the use of a species-selective grid (i.e., trawls equipped with a Nordmore-type sorting grid with a 35-mm bar distance, depicted in Fig.1c) is mandatory in Swedish national waters. This legislation was introduced with the aim to significantly reduce the fishing mortality of the juveniles and adults of local populations of demersal fish species such as cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) and to protect habitats sensitive to trawling disturbance (Valentinsson, unpubl.). In 2005, 34% of Norway lobster catches were landed by trawls with sorting grids, 46% by conventional trawls, and 20% by creels. The compositions of the catches obtained using the three fishing methods are presented in Figure 2.

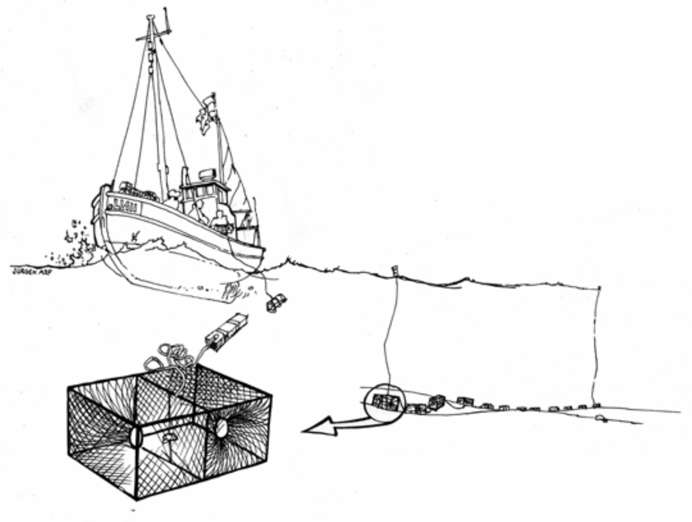

Fig.1a)

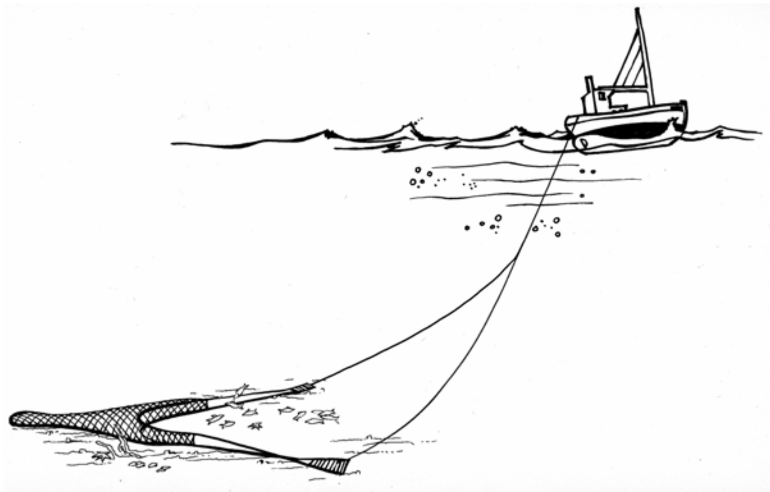

Fig.1b)

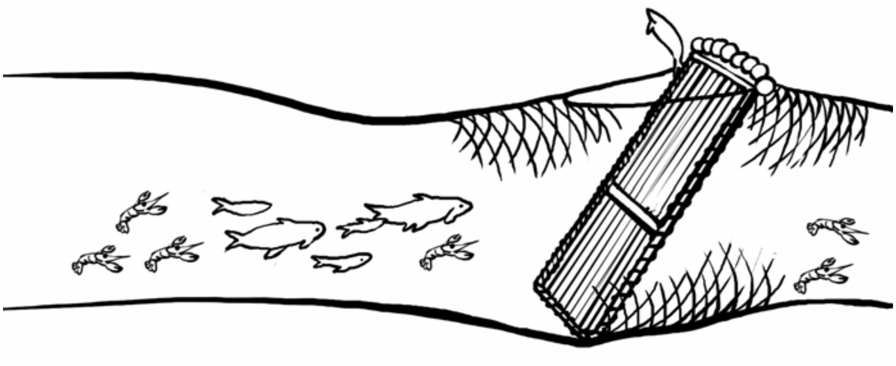

Fig. 1c)

Figure 1. Fishing gear used along the Swedish west coast to target Norway lobster a) creel, b) conventional single trawl, and c) species-selective grid trawl.

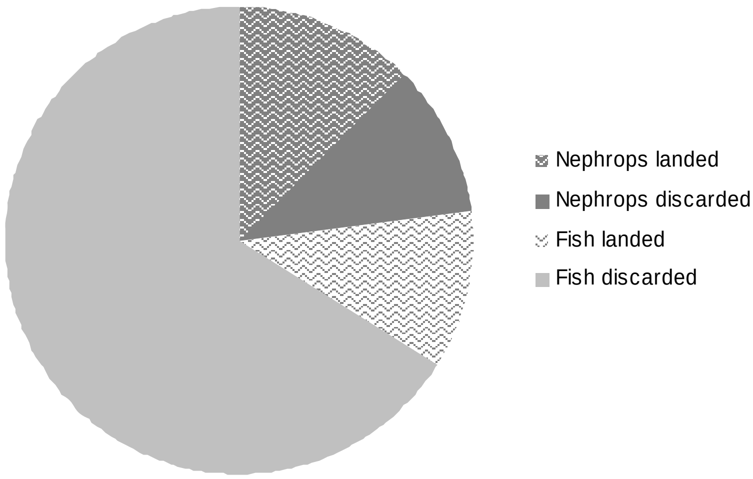

Fig. 2a)

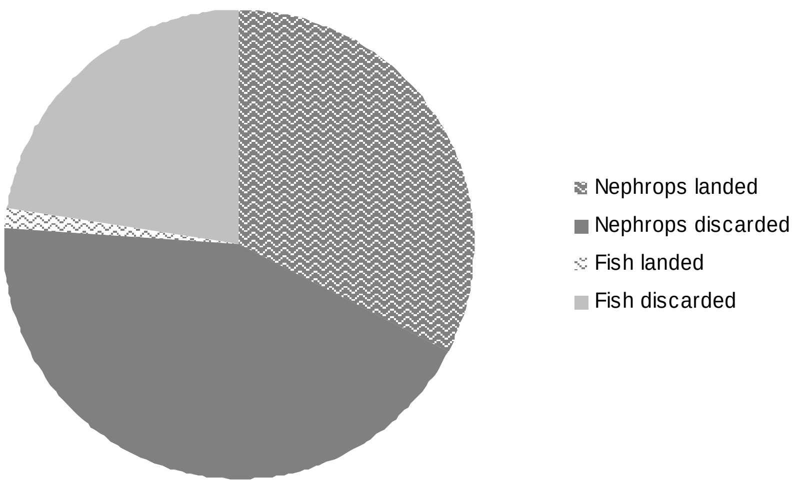

Fig. 2b)

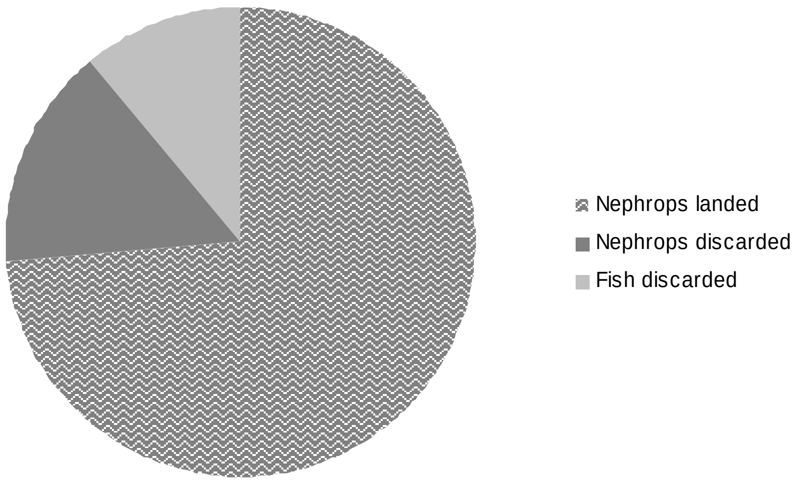

Fig 2c)

Fig. 2 Composition of the catches obtained using the three fishing methods: a) conventional *Nephrops* trawl (90-mm diamond mesh codend), b) selective *Nephrops* trawl (35-mm sorting grid and 70-mm square mesh codend), and c) *Nephrops* creels. Note that no estimates of natural and discard mortality are included here as is done later. Average values for 2004-2005.

Goal and scope

This study mainly aimed to quantify the resource use and environmental impact caused by the production and consumption of Norway lobsters caught by creels and trawls. A secondary goal was to evaluate the environmental consequences of the 2004 introduction of a fishing regulation, the mandatory species-selective grid in the *Nephrops* trawl fishery. Norway lobster was chosen as the subject species because it is the economically most important fishery in the Kattegat, and due to the availability of marine habitat maps for this area. A method to quantify the seafloor impact of active fishing gear was developed in a previous study (Nilsson and Ziegler 2006). The use of the method in the Norway lobster case study represents its first application in a seafood LCA. The functional unit was 300 g of Norway lobster tails (three servings) of average-sized Norway lobsters bought boiled from a seafood retailer in Göteborg to be consumed cold in a private households. With a product exchange of 30%, the functional unit corresponds to one kilogram of landed Norway lobsters. Three different fishing methods were included: creeling, conventional trawling and species-selective trawling. The life cycle on land was assumed to be identical for Norway lobsters regardless as to how they were caught. The product was followed starting from the production of supply materials, such as fuel, electricity, and packaging materials, through the fishery, transport, retail, and consumer phases. The life cycle ends with municipal sewage treatment which releases the nutrients contained in the Norway lobsters back to the sea.

Material and methods

Data sources

A questionnaire asking about approximate fuel consumption, catches, gear types, gear material, anti-fouling and other chemical agents, and product quality was sent to the 78 fishermen who according to official fishery statistics, had reported landings of more than 1000 kg of Norway lobster in two consecutive years, 2002 and 2003. We chose to target fishermen having Norway lobster fishery as their main occupation. Answers from 19 of these fishermen were used, 12 of whom used creels and 7 conventional trawls. The Swedish Board of Fisheries provided data from their statistical database which is based on logbook data concerning all landings of *Nephrops* in the Kattegat and Skagerrak in 2005. Data concerning the composition of the catch using the species-selective trawl were gathered via on-board observer programs in 2004 and 2005, reported in Valentinsson (unpubl.). Additional data were collected from companies involved in the production chain of Norway lobsters and LCA databases, primarily Ecoinvent v.1.2 (Anon. 2000) were used to obtain data concerning, for example diesel, electricity and packaging paper production. Emissions produced by diesel combustion were modeled as by Ziegler and Hansson (2003), for more details, see Ziegler (2006).

Seafloor impact assessment

The questionnaire mentioned above also asked about approximate gear dimensions, that is, the width of the trawl opening and length of the trawl boards and the width and length of the creels. From these data, we calculated an index of area swept per hour trawled. The fishing effort data (hours trawled) for different gear types provided by the National Board of Fisheries were multiplied by the gear index of each trawl type considered to be used to target Norway lobster, and then divided by the total catch reported in the same data material in order to obtain a rough estimate of the average seafloor area swept per unit of landed catch in the trawl fishery.

Nilsson and Ziegler (2006) developed a methodology for spatially analyzing of demersal fishing effort data which was applied in the present case study. GIS analysis was hence performed in order to assess the intensity and biological impact of the seafloor impact on the benthic habitats occurring in the area. Fishing positions (gear set position) in longitude and latitude were transformed to decimal degrees and the data were then imported into the ArcMap 9.0 (ESRI 2004) GIS software package. A map of marine habitats classified according to the European Nature Information System (EUNIS) (Anon. 2002), also used in Nilsson and Ziegler (2006), was also imported. The fishing effort dataset was then overlaid with the habitat map and fishing intensity was analyzed in 5 km x 5 km squares by applying the neighborhood statistics function in the ArcMap extension Spatial Analyst, both for the entire area and for each marine habitat type separately. The analysis produced estimates of the total proportions of each habitat and of the entire area affected by fishing and fishing intensity (for each habitat and for the entire area). The biological impact of the found fishing intensities was evaluated using a British database (MarLIN) containing information on the sensitivity and recoverability of marine species and habitats (Anon. 2004) as was done in Nilsson and Ziegler (2006).

With regard to the species-selective trawling, the additional areas protected from trawling were not modeled. It was assumed that the seafloor impact per unit of landed catch was the same and the only difference modeled was the different catch composition.

For the creel fishery, the average area of a creel was determined from the questionnaire, as was the average number of creels used per single occasion. These figures and the total number of efforts that had occurred in the area (Skagerrak and Kattegat) in a year were multiplied, and the result was then divided by the total Norway lobster catch to obtain the average seafloor area used per unit of landed catch in the creel fishery. Intensity was not analyzed in the same way as for the trawl fishery, as the total area affected was so much smaller.

Discard

Data concerning discards from conventional *Nephrops* trawls were provided by onboard observer programs, examining the catches of commercial fishing vessels , and were expressed in terms of kg of undersized *Nephrops* and fish discarded per kg landed for the gear types and hauls targeting *Nephrops* (Walther, pers. comm.). The main species discarded are described as are the biological and environmental consequences of this activity. Discard data for the species-selective trawl were gathered from the first evaluation of the regulation introduced in 2004 (Valentinsson, unpubl.). These data were gathered as part of the same onboard observer programme, examining the catches of commercial vessels using both conventional and species-selective trawls in 2004 and 2005. Discard mortality estimates for *Nephrops* were found in Ulmestrand *et al*. (1998).

A brief introduction to the life cycle assessment method

Life Cycle Assessment is a method for the environmental assessment of products and processes, standardized in ISO 14040 (ISO 2002). The performance of an LCA is divided into four main parts: goal and scope definition, inventory analysis, impact assessment and interpretation of results. In the goal and scope definition, the system to be studied and the purpose of the study is defined. System boundaries are chosen, preferably reflecting the boundary between the natural and the technical systems under study, that is, normally starting with extraction of raw materials and ending with waste treatment. The inventory analysis consists of gathering of data concerning the resource use, energy consumption, emissions and products resulting from each activity in the production chain. All in- and outflows are then calculated on the basis of a unit of the product called the functional unit. The choice of this unit should represent the function of the product. Some activities may have more than one product; in such cases, the total environmental impact is often divided between the main product and the by-products, in a procedure known as allocation. Allocation is based on the most relevant relationship between the main product and by- products in each case in terms of, for example, mass, energy content, or economic value. Another approach is to include the by-products in the system and separately assess another production system for each by-product, which can then be subtracted from the original system to obtain results for the main product. This latter approach is called system expansion and is recommended by ISO.

The first result of an LCA is a matrix of inventory results, in which the calculated values for each phase of the life cycle as well as the total values are presented for a number of substances, categorized as resources from ground, resources from water, emissions to air, emissions to water, and products. To simplify this matrix and to get an idea of what kind of environmental impact these emissions cause, characterization methods are used that weight together all emissions causing, for example, global warming, acidification, toxicity, eutrophication, photochemical ozone formation and stratospheric ozone depletion. This characterization, together with qualitative assessment of types of environmental impact that cannot be characterized, is called impact assessment. Qualitative assessment means that when no reliable method to quantify a category of environmental impact exists, or data are lacking, it can be assessed qualitatively. After impact assessment is completed, the interpretation of results, identification of key figures and initial assumptions and a sensitivity analysis follows to complete the LCA. In the sensitivity analysis, key figures are varied and the dependence of the results on certain data is analyzed in relation to the quality of those data. There are many handbooks explaining step-by-step how to conduct an LCA (Berlin 2003, Baumann and Tillman 2004, Hauschild and Wenzel 1997, Wenzel *et al*. 1997). The present LCA was performed using the software SimaPro Analyst 6.0.4 (PRé Consultants 2004) and the characterization method chosen was the one developed at the Institute of Environmental Sciences (CML) at Leiden University, the Netherlands, CML baseline 2000 (v. 2.03). Of the impact categories included in the CML method, freshwater, terrestrial and human toxicity were excluded due to uncertainties in the results identified by Ziegler (2006), and ozone depletion potential was excluded because of data gaps described in the same report. For more details concerning the methodology used in this case study, see Ziegler (2006).

Results

Energy use

Fig. 3 shows that the fishery itself is the phase in which most energy is consumed. Energy use after landing represents just 10% of the total life cycle energy use for conventionally trawled, 19% for selectively trawled and 32% for creel-fished Norway lobsters. Energy use in the fishing phase is extraordinary. To catch 1 kg of Norway lobsters using conventional trawling, 325 MJ are used in the form of diesel. For the creel fishery this figure is 80 MJ (of which approximately 10% comes from the bait herring fishery). Regarding species-selective trawling, its different catch composition makes it much more resource efficient than conventional trawling and the species-selective trawl fishery requires just over 150 MJ to catch the same amount of Norway lobster. In the creel fishery Norway lobster represents 97% by weight and 99% by value of the catch, and 2.2 l of diesel were used per kg of *Nephrops* landed. In the conventional trawl fishery Norway lobster represents 27% by weight and 59% by value of the catch, and 9.0 l of diesel were used per kg of *Nephrops* landed. Finally, in the selective trawl fishery Norway lobster represents 93% by weight and 98% by value, and 4.3 l of diesel were used per kg landed, assuming the same fuel use *per kg of landed catch* as in conventional trawling. Obviously, there is a pronounced difference in energy use between the fishing methods, as can be seen in Fig. 4.

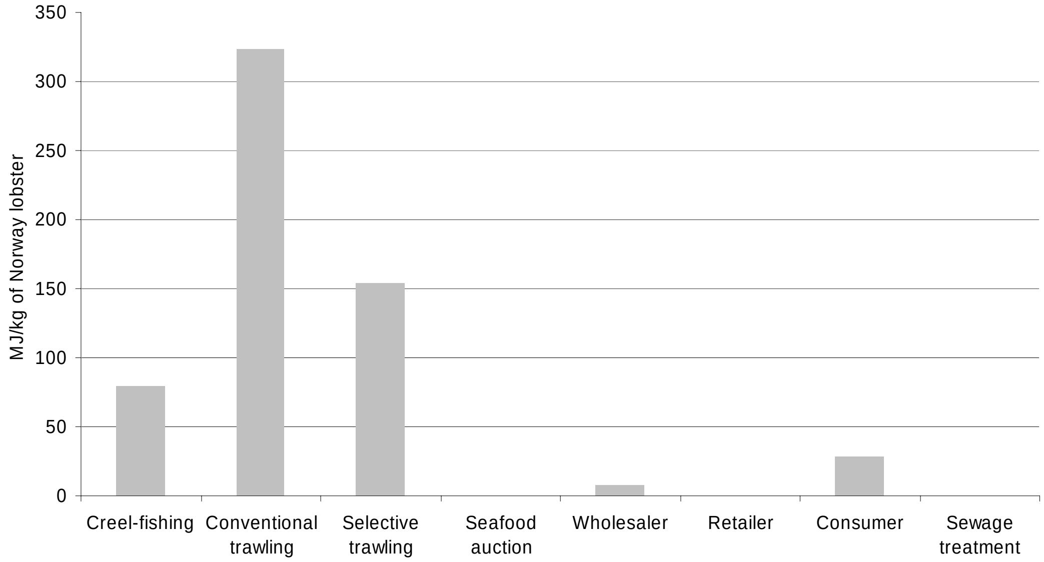

Fig. 3. Energy use in the life cycle of a kilogram of Norway lobster. Creel fishing, conventional trawling, and selective trawling represent alternative fishing methods.

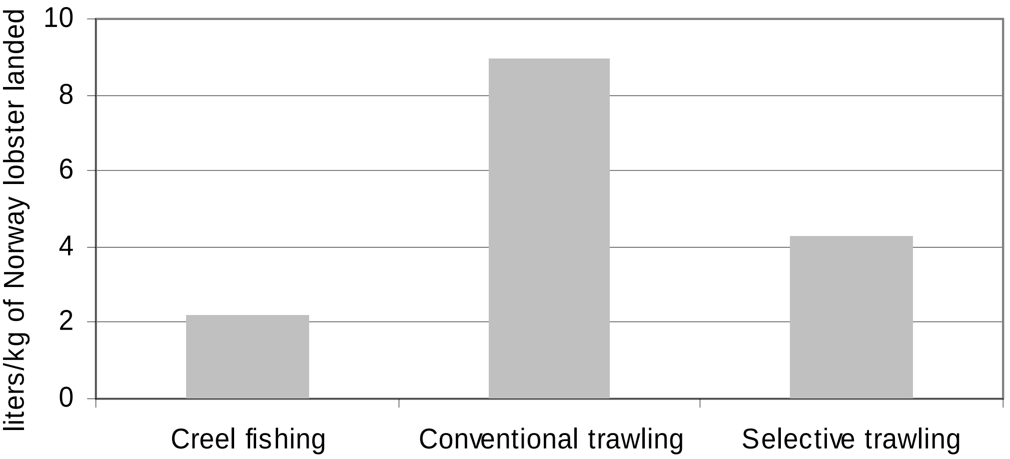

Fig. 4. Fuel consumption in Norway lobster fisheries using the three fishing methods.

Seafloor impact assessment

The seafloor area swept by conventional *Nephrops* trawls was calculated to be approximately 15,000 m^2 per kg *of catch*. After economic allocation (59% of the economic value of the catch was represented by *Nephrops*) and consideration that only 27% of the catch (by weight) was Norway lobster, the result was that 33,000 m^2 were swept per kg of *Nephrops* landed (corresponding to a square 182 x 182 m in size).

Results of the GIS analysis indicated that 29% of the total Kattegat area was affected by the trawl fishery in 2003. In muddy seafloor areas that are the natural habitat of Norway lobsters, 86% of the area was affected by the fishery. Other habitats affected were sandy habitats (58% affected), combination sediments (59% affected) and deep rocky habitats (100% affected). The last result is partly due to the small total size and patchy distribution of this habitat in relation to the size of the analyzed squares (which was inescapable due to the resolution of the trawl effort data); there could have been overestimation, so the result should not be over interpreted. Nevertheless, the borders between muddy and rocky areas are known to be good fishing grounds for both Norway lobsters and for some important fish by-catch species. Intensity, it was likewise highest in muddy areas. Muddy areas were on average swept 2.5 ± 2.9 times per year; a considerable proportion of the muddy habitats (36%) was swept more than twice per year and 15% was swept more than four times per year. Disturbance intensity was lower in the other habitats, including the deep rocky ones. Almost the entire remaining area was affected less often than twice per year by these trawlers.

The recoverability of muddy habitats from fishing disturbance, according to the MarLIN database (Anon. 2004), is high, indicating complete recovery in six months to five years after a single fishing event. This would indicate than any muddy area being affected more often than twice per year remains in a continuously disturbed condition, which in this case corresponded to 36% of the habitat (or 1242 km^2). Hence, 1242 km^2 are kept in a permanently altered condition due to *Nephrops* trawling that lands approximately 246 tons of Norway lobster from the area, indicating that approximately 3000 m^2 per kg of Norway lobster landed (corresponding to a square 55 x 55 m in size) are permanently disturbed, given the current level and distribution of conventional trawl fishing effort.

The different composition of the catches of the species-selective trawl led to highly different results in all categories (as described for energy use), including seafloor use. Using the same figure for seafloor swept per kilogram of catch landed as for the conventional trawl, the different catch composition of the selective trawl (Norway lobsters accounting for 98% of the economic value of the catch and 93% of its weight) gives a seafloor area swept per kilogram of Norway lobster landed by selective trawls of 15,600 m^2.

The area impacted by the creels was much smaller. The entire west coast creel fishery, landing 20% of the total lobster catch affected the same seafloor area as did one hour of trawling. The seafloor affected by creels per kg of catch (99% of the economic value of the catch comes from Norway lobsters) was calculated to be 1.8 m^2. Due to the enormous difference in seafloor impact between the trawl and creel fisheries, no effort was made to analyze intensity as was done for the trawl fishery.

Discard

The amount of discard of all species killed in the conventional trawl fishery was calculated to be 4.5 kg per kg of *Nephrops* landed, of which 0.4 kg was undersized *Nephrops* and 4.1 kg was undersized fish. The natural mortality of Norway lobsters (25%) and fish (20%) was accounted for as were the different discard mortality rates of the different species (i.e., discard mortality of Norway lobster 75%, of fish 100%). The main species discarded during conventional trawling were cod (*Gadus morhua*), flounder (*Platichthys flesus*), *Nephrops*, dab (*Limanda limanda*), whiting (*Merlangius merlangus*), plaice (*Pleuronectes platessa*), long rough dab (*Hippoglossoides platessoides*), edible crab (*Cancer pagurus*), gurnard (*Eutriglia gurnardus*), and hake (*Merluccius merluccius*).

Species-selective trawling led to considerably lower discards and landed by-catch, a total of 1.35 kg per kg of *Nephrops* landed, of which 0.82 kg was undersized *Nephrops* and 0.53 kg was undersized fish. The discard of undersized fish was hence 87% lower and total discards (i.e., including *Nephrops* discards) were 70% lower than in conventional trawling. The higher discard of *Nephrops* is due to the fact that the selective fishery occurs mainly in national waters located closer to shore that are hence fished more intensely. The landed by-catch decreased from 73% to 6.6% of total catch by weight (Valentinsson, unpubl.). The main species discarded during selective trawling were *Nephrops*, dab (*Limanda limanda*), long rough dab (*Hippoglossoides platessoides*), plaice (*Pleuronectes platessa*), cod (*Gadus morhua*), whiting (*Merlangius merlangus*), witch (*Glyptocephalus cynoglossus*), hake (*Merluccius merluccius*), flounder (*Platichthys flesus*), and gurnard (*Eutriglia gurnardus*).

Discards in the creel fishery were even lower, 0.36 kg per kg of Norway lobster landed (Anon. 2006); of this, 0.21 kg was undersized *Nephrops* and 0.15 kg was undersized fish. A large part of the fish can be assumed to die, while 99% of the discarded creel-caught lobsters survive (Wileman et al. 1999), hence approximately 0.15 kg (assuming 100% mortality for lack of other figures) of fish discard is killed per kg of creel-caught *Nephrops* landed. In the creel fishery the main species discarded were *Nephrops*, cod, sea scorpion (*Myoxocephalus scorpius*), swimming crab (*Liocarcinus depurator*), spider crab (*Hyas* sp.), edible crab (*Cancer pagurus*), poor cod (*Trisopterus minutus*), whelk (*Neptunea antiqua*), hermit crab (*Pagurus bernhardus*), and squat lobster (*Munida rugosa*).

The discarding of these mostly commercially valuable species is a waste not only of biological but also of economic resources, as these individuals could have grown and become part of the commercial catch in one or several years.

Impact Assessment results

The process of fishing is dominant in terms of environmental impact in all three cases, more markedly so for conventionally trawled *Nephrops* than for those caught by selective trawls or creels. Diesel combustion and diesel production determine this result. Other important phases are the transport home from the retailer and bait and gear production for the creel fishery. In one impact category, photochemical oxidation, the impact of transport home even exceeds the creel fishery itself (Fig. 5 and Table 1). The results of the impact assessment are presented in Fig. 5 and in Table 1.

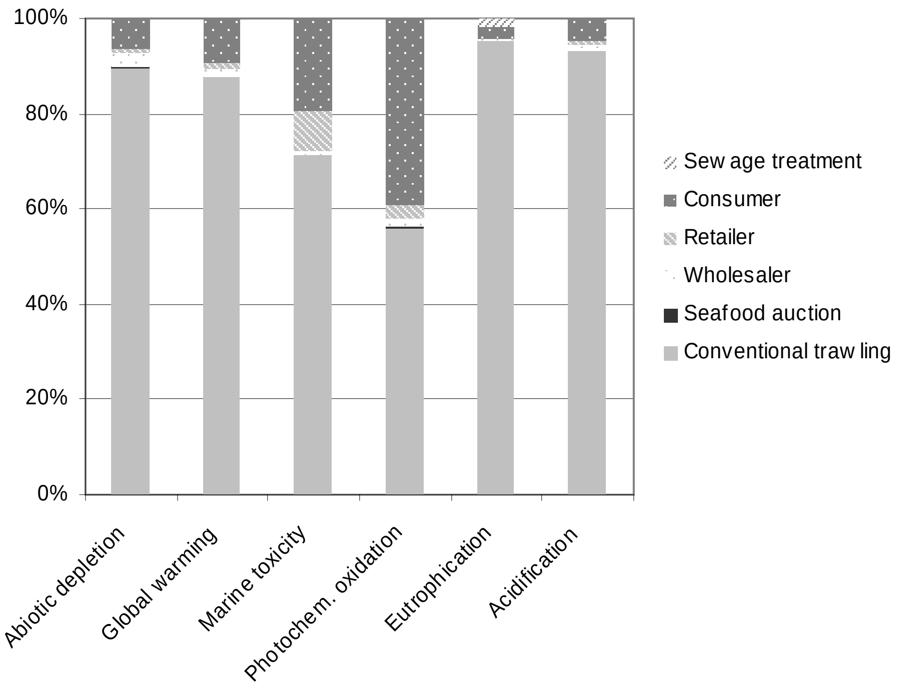

Fig. 5a)

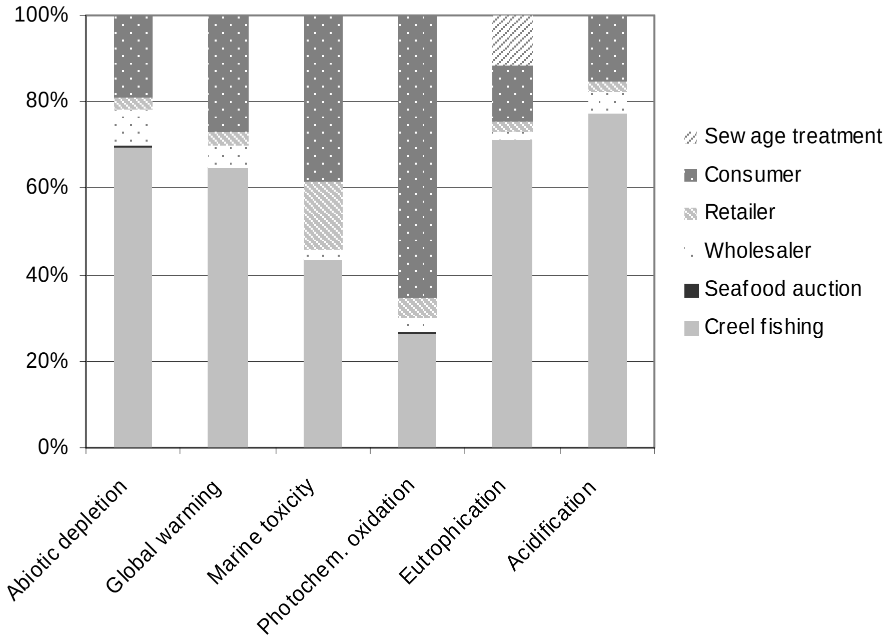

Fig. 5b)

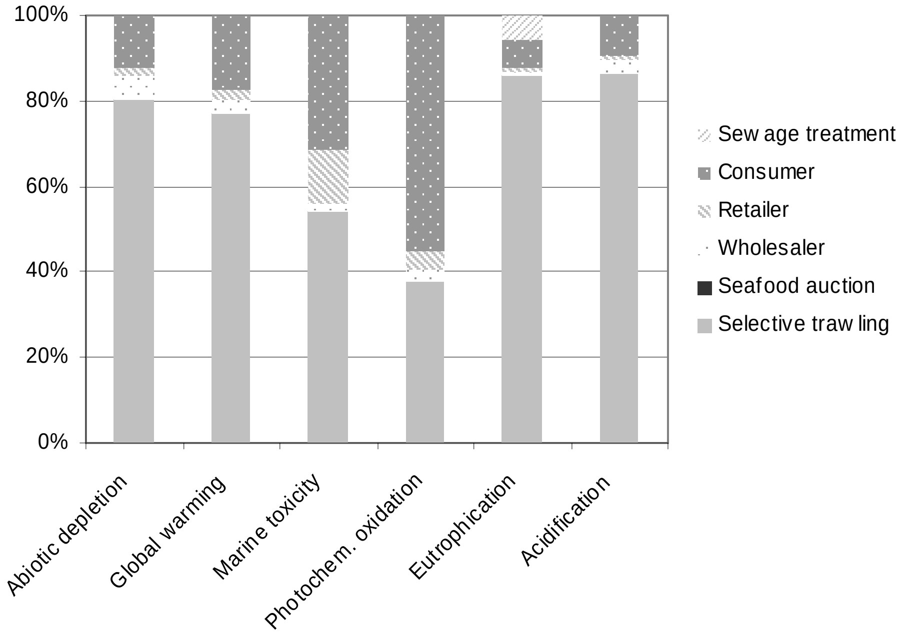

Fig. 5c)

Fig. 5. Characterized LCA results for a) conventional trawling, b) creel fishing, and c) selective trawling.

Table 1. The three most important processes in each impact category.

Impact category	Fishing gear	Most important process	Second most important process	Third most important process
Global Warming	Conv. trawl	Diesel combustion	Diesel production	Home transport
Global Warming	Selective trawl	Diesel combustion	Home transport	Diesel production
Global Warming	Creel	Diesel combustion	Home transport	Diesel production
Eutrophication	Conv. trawl	Diesel combustion	Diesel production	Home transport
Eutrophication	Selective trawl	Diesel combustion	Diesel production	Home transport
Eutrophication	Creel	Diesel combustion	Home transport	Diesel production
Acidification	Conv. trawl	Diesel combustion	Diesel production	Home transport
Acidification	Selective trawl	Diesel combustion	Diesel production	Home transport
Acidification	Creel	Diesel combustion	Diesel production	Home transport
Marine toxicity	Conv. trawl	Diesel production	Diesel comb./ Antifouling emissions	Municipal waste incineration
Marine toxicity	Selective trawl	Diesel production	Diesel comb./ Antifouling emissions	Municipal waste incineration
Marine toxicity	Creel	Diesel production	Municipal waste incineration	Home transport
Photochemical oxidation	Conv. trawl	Diesel production	Home transport	Diesel combustion
Photochemical oxidation	Selective trawl	Home transport	Diesel production	Diesel combustion
Photochemical oxidation	Creel	Home transport	Diesel production	Diesel combustion
Abiotic resource depletion	Conv. trawl	Diesel production	Home transport	PP/LPG production[1]
Abiotic resource depletion	Selective trawl	Diesel production	Home transport	PP/LPG production[1]
Abiotic resource depletion	Creel	Diesel production	Home transport	PP/LPG production[1]

[1] At wholesaler

Sensitivity analysis

We conducted a sensitivity analysis of the five aspects considered to have the greatest impact on the overall results: fuel use, two allocation decisions, product exchange, impact assessment method, and background data chosen. Fuel use varied one standard deviation (SD) above and below the mean. The ranges overlapped slightly, and when the fuel consumption in conventional trawling was one SD lower and in the creel fishery one SD higher than the mean, the two fisheries produced similar amounts of global warming emissions. However, this was considered an unlikely scenario due to the significant difference between the two. The range of conventional trawling was 14-50 kg CO_2 eq. (mean: 32 kg CO_2 eq), and the range of creel fishing was 7.0-15 kg CO_2 eq (mean: 11 kg CO_2 eq) . Selective trawling produced emissions of 8.6-26 kg CO_2 eq (mean: 17 kg CO_2 eq) and overlapped more with creel fishing than did conventional trawling. The selective trawling mean emissions ranked between those of the other two gear types, as before, but with one standard deviation lower fuel consumption, this method produced less global warming emissions than did average creel-fishing. In conclusion, variation of this important aspect was great, but the differences between the three fishing methods were likewise great, which is why we believe that the general conclusions are robust. More detailed data concerning the fuel consumption in these fisheries would be useful. The next aspect studied in the sensitivity analysis was the data underlying two allocation decisions.

Allocating based on the same prices as used previously but with the catch composition as reported in the questionnaires, in which the creel fishery was found to use 2.2 ± 1.2 l diesel per kg of Norway lobster landed (*Nephrops* representing 86% of the catch value as opposed to 99% as reported in the logbook-based fishery statistics). Conventional trawling used 8.6 ± 4.2 l diesel per kg of Norway lobster landed (*Nephrops* representing 70% of the catch value as opposed to 59% as reported in the statistics). The ranges do not overlap and the difference between the two is statistically significant (Fig. 6). If allocation were based on the landings as recorded in the logbooks, in both cases it would differ by approximately 12%; likewise the difference between the fishing methods would increase further when allocating in this way, global warming emissions increasing from 32 to 37 kg CO_2 eq for conventional trawling and decreasing from 11 to 10 kg CO_2 eq for creel fishing.

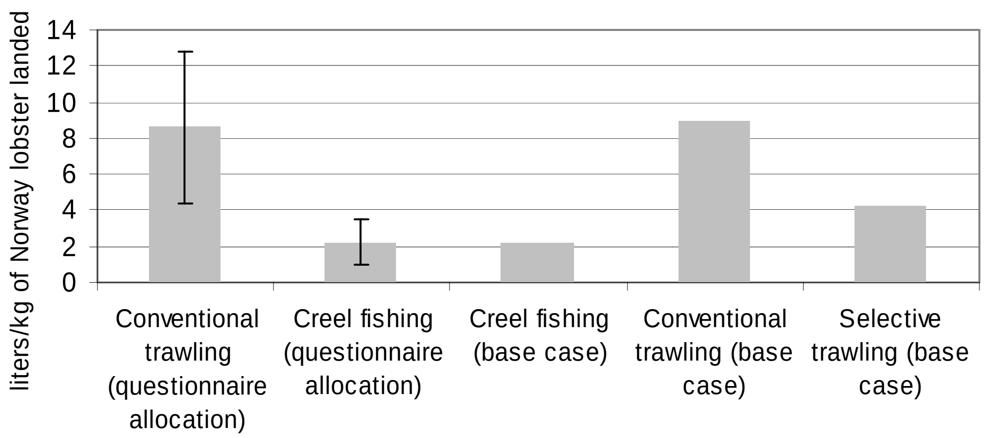

Fig. 6. Fuel consumption in the *Nephrops* fisheries, allocated according to catch composition as reported in the questionnaires (error bars represent standard deviation).

Allocating smaller parts (10% and 50% instead of 100%) of the total environmental impact caused by transport home to the Norway lobsters caused no major changes in the results, but decreased the importance of the home transport especially in terms of photochemical oxidation and global warming potential. The importance of the third aspect, product exchange, was greater. Global warming emissions decreased by 25% when the product exchange was increased from 30% (as reported in literature) to 40% (as found in our own research). The fourth aspect was the impact assessment method, which was included due to the odd results initially found in the freshwater, terrestrial and human toxicity categories. Ecoindicator 99 was compared with the CML method, and it was concluded that the impact categories that are comparable between the two methods did correspond fairly well, and that the main results would not have changed had Ecoindicator 99 been used in the first place. To further analyze the reasons for the results in the toxicity categories, the Ecoinvent data concerning LDPE, diesel and passenger car transportation were replaced with data from the BUWAL database as the fifth and last aspect to be studied. In the case of diesel production, the data choice had only a minor impact, while the use of BUWAL data led to a 23% increase in global warming emissions of passenger car transport, making it account for 11% rather than 9% of the overall global warming potential of the product life cycle. Choosing new LDPE data completely altered the results for the toxicity categories, as discussed by Ziegler (2006), which is the reason why these categories were excluded from the present study.

Discussion

Discards

The discard level in conventional *Nephrops* trawl fisheries is a recognized problem. Actually, the northeast Atlantic trawl fishery for *Nephrops norvegicus* has the fifth highest discard ratio in the world (Catchpole et al., in press). The weighted average discard for shrimp trawling (of which *Nephrops* trawling by definition is part) is 62%, the highest of all major types of fisheries in the world (Kelleher 2005). The amounts discarded in the studied fishery were even higher: more than four times the amount landed, while the number of individuals killed per individual landed were even higher, since the discarded specimens were smaller. With the exception of creel-caught *Nephrops* (which survives discarding, see below) discarding is a waste of a limited biological resource. Almost all of the individuals discarded will die and they could, if left in the sea, have been part of future catches. The most critical part of the discard comprises undersized Norway lobsters and groundfish species such as cod and haddock. Cod stocks are at historically low levels in this area, and since 2003, the International Council for the Exploration of the Sea (ICES) has repeatedly recommended a moratorium on cod fishing. Therefore, the introduction of the species-selective trawl, which decouples the *Nephrops* fishery from the groundfish fishery and makes the *Nephrops* fishery less dependant on the availability of fish quotas (Valentinsson, unpubl.), is very positive. With regard to eutrophication potential, even though the landed catch represents an outtake of nutrients from the sea, this fishery causes an increase in the biological turnover of nutrients and contributes to eutrophication in the area due to the high amount of discard.

Discarding in the creel fishery has been much less studied. In 2005 a sampling was done on 18 fishing trips on creel fishing vessels to study the catch composition (Anon. 2006, data presented in Fig. 2c). Those data were used in the present study and indicated that the overall discard level was much lower in the creel fishery than in the two trawl fisheries. In addition, discard survival is higher, especially in the case of *Nephrops* for which it has been estimated at 99% (Wileman *et al.* 1999). Trawling with the use of a sorting grid led to a 67% decrease in the discard of undersized fish and a 27% decrease in overall discards (i.e., including *Nephrops* discard). Equally important is the catch composition of the selective trawl, for which 93% (by weight) of the landed catch is Norway lobster as opposed to 27% in the case of conventional trawls.

The species-selective trawl represents a great improvement with regard to one of the most crucial environmental aspects of *Nephrops* trawling. It is thus desirable to continue this positive development by making sure that selective trawls are used more widely in the future.

Another positive conclusion from the first evaluation of the grid introduction is that it seems to have caused no loss of commercial-sized *Nephrops*, rather the amount landed per unit of effort with selective trawls being the highest of all trawl categories targeting Norway lobster.

Seafloor impact

The seafloor area swept and permanently affected by trawls per kilogram of trawled Norway lobster may seem large. It should be considered that *Nephrops* trawling is the dominant type of demersal trawling occurring in the area, but not the only one and that Danish fishermen land more Norway lobster than do Swedes in this area. This implies that the total impact of demersal fishing is much greater than is presented here, where the intention was to relate the impact to a functional unit of Norway lobsters. However, it is impossible to analyze Danish fishing effort in the same way, since their effort is not reported at the same geographical resolution. It should also be kept in mind that the recovery time indicated as high in MarLIN is six months to five years, so the use of six months (more than twice per year = permanently disturbed) leads to a very conservative estimate of the seafloor impact. The species-selective trawl caused much less seafloor impact per kg of Norway lobster landed due to the cleaner catch composition, with a much higher percentage of the landings consisting of Norway lobster.

The impact of a creel landing on the seafloor when it is set is probably smaller per square meter than when the same area is swept by a trawl, but due to a lack of specific data concerning this matter and the great difference in area impacted by trawls and creels per kg landed, it was not further analyzed.

Safety and working conditions

Trawling is a more automated procedure than creel-fishing is. Setting and hauling creels is normally done manually by a person on deck, and working conditions are often far from optimal from both ergonomic and safety points of view (Aasjord, pers. comm.). Fishing is a high-risk profession, and fatal accidents are more common on smaller vessels deploying passive fishing gear than on larger, more industrialized vessels; as well, the accidents that do occur tend to be less serious accidents on larger vessels such as trawlers (Aasjord, pers. comm.).

Ghost fishing

An additional risk is the loss of gear or gear material, a risk that is higher in creel fishing (Anon. 2001) than in trawling and may partly explain of the high use of gear material in this fishery. Lost creels and nylon netting can keep trapping animals, especially if there is still bait inside, subsequently killing them, a process termed ghost-fishing (Anon. 2001, Anon. 2003). Ghost-fishing is a problem with some passive fishing gear types, especially gillnets. The use of degradable gear materials in creels and gillnets has been proposed as a means to mitigate this risk (Anon. 2001).

Energy use

The fishing phase, with its high fuel consumption, dominated the life cycle in the case of both for creel fishing and trawling for Norway lobster, as has been shown for many other types of seafood (Thrane 2004a, Thrane 2004b, Thrane 2006, Ziegler et al. 2003, Ziegler and Nilsson, unpubl). The difference is that the fishing phase of conventional trawling for Norway lobster, was even more important than later life cycle phases due to the extraordinary fuel consumption in this fishery, 9 l of diesel being consumed per kg of Norway lobster landed. Thrane (2004a) found a fuel consumption of approximately 6 l per kg of Norway lobster landed in Danish fisheries while Tyedmers (2001) found a much lower energy consumption: 37 MJ/kg corresponding to less than 1 l of diesel per kg. The low consumption found in the latter study was probably because Norway lobster was not the primary target species of the investigated fishery (which was cod) and that mass allocation was used to divide the fuel use between the cod and Norway lobster catch. Thrane, in contrast, used system expansion to avoid allocation between catch and by-catch, so none of these figures are really comparable. Had Thrane used economic allocation instead, the fuel consumption would have been approximately 4 l per kg of *Nephrops* (Thrane 2006), less than half that found in the present study. A considerable improvement option with regard to energy use lies in the more widespread use of creels and the species-selective grid, which used 4.3 l per kg of Norway lobster caught, the improvements deriving solely from the cleaner catch composition compared to that of conventional trawls.

Baiting

The use of bait was responsible for 10% of the total energy consumption of creel fishing and 5% of the global warming emissions produced throughout the life cycle of the creel-fished lobsters. The amounts of bait used were higher than the amount of *Nephrops* caught. As small (undersized) lobsters can enter the creels to feed on the bait and then leave the creels again, this could be viewed as an input of nutrients to the marine ecosystem or as a type of semi-aquaculture, in whichsmall lobsters are fed herring to grow to commercial size. Much of the bait however, is left in the creels when they are hauled up and seabirds happily consume it when discarded (it has to be replaced since it does not “smell” after a couple of days in the water). No studies have examined the proportion of bait actually consumed by the catch and the proportion leaving the creels with undersized specimens, but it can be assumed to be considerable. The use of artificial bait (flour-based dough containing fish oil) could be an improvement option to consider for the creel fishery.

Impact on Norway lobster stocks

The use of the Norway lobster stock on the Swedish west coast is currently considered to be sustainable, but it is recommended that fishing mortality should not increase due to uncertainty about the stock status in relation to threshold values (Ask and Westerberg 2006). The composition of the landed *Nephrops* catch is biased towards males, and both the creel and trawl landings comprise approximately 70% males and 30% females (Anon. 2006). Of the females landed, more are found to be berried (carrying roe) in creel than in trawl catches. Berried females normally stay in their burrows, but they seem to be attracted by the bait and therefore enter the creels. This overrepresentation of berried females in the catches is discussed as one potential negative aspect of creel fisheries, since there is a risk of recruitment overfishing (i.e. that not enough eggs are produced) should the creel fisheries grow rapidly. Since the discard survival is very high for creel-fished *Nephrops* (Wileman et al. 1999), one way to mitigate this could be to protect berried females (as is done in the Swedish fishery for European lobster, *Homarus gammarus*).

Product quality

A study of the quality of Norway lobsters caught with creels and conventional trawls showed that there was a significant difference between the quality of Norway lobsters caught by creels and trawls (Evenbratt 2005). Creel-caught lobsters were in a better condition from the beginning and their quality decreased more slowly than their trawled relatives, they were also larger (all of which explains why they achieve higher prices). The quality assessment method used was QIM (Quality Index Method), a sensory evaluation method. The scheme for Norway lobster is still under development and not fully validated, but was kindly made available by

RIVO-DLO, the Netherlands (Schelvis, pers. comm.). In a comparative LCA one would ideally like the products to be identical with regard to function and quality. In this case the quality of the products of the two fishing methods was shown *not* to be identical. The fishing method with the least resource use and emissions also had the highest catch quality, meaning that more of the catch will reach the end consumer and less of it end up as product waste. This underlines the previous conclusion in this study that creel-fishing of lobsters is less resource-intensive than trawling. Catch quality differences between conventional and species-selective trawls have not been evaluated.

Evaluation of the new gear regulations introduced in 2004

Comparing conventional and grid trawls clearly demonstrate that the new gear technology offers great improvement potential. The only two changes we considered were lower discard and changed catch composition, and these two aspects resulted in major changes in LCA results. It seems likely, however, that other improvements have occurred that are more difficult to quantify. The landings per unit of effort (LPUE) achieved with selective trawls were the highest of all the *Nephrops* trawl types analyzed in 2004 and 2005 (Valentinsson, unpubl.). Moreover, the distances from port are shorter since grid use is mandatory in national waters which are located within 3-4 nautical miles of the coastline. These two latter differences influence the resource use per kg of catch landed. In the present study, however, these aspects were assumed to be identical for the two trawl fisheries, so the difference is likely even greater than is indicated here.

Conclusions

Major differences between the environmental performance of creel and trawl fisheries for Norway lobster were demonstrated. Comparing conventional and species-selective trawls has shown how LCA, in a relatively straightforward way, can be used to evaluate the environmental consequences of new technical regulations imposed on fisheries, once the data for a fishery are gathered. Consequently, there are great potentials for improvement by replacing conventional trawls with creels or species-selective trawls. A hypothetical future situation using currently available technology, in which 50% of Norway lobster landings are caught using selective trawls and 50% using creels (compared to 34% caught using selective trawls, 46% conventional trawls and 20% creels in 2005) would lead to 62% less seafloor impact, 84% less fish discard and 11% less discard of undersized *Nephrops* as well as a 46% lower fuel consumption, while providing consumers with the same amount of Norway lobsters.

Acknowledgements

We would like to thank all those who spent time helping us gather the data for this study. First and foremost, we thank the 19 anonymous fishermen who most kindly provided us with data by completing the questionnaire. We would also like to thank all those who helped gather data regarding the life cycle on land and all the on-board observers at the Institute of Marine Research, Lysekil, who helped us with data collection. The Knowledge Foundation is acknowledged for financial support.

References

Anon., 2000. Ecoinvent 1.2, 2000. Swiss Centre for Life Cycle Inventories. http://www.ecoinvent.ch/

Anon., 2001. Småskaligt kustfiske och insjöfiske: en analys (Small scale fisheries and lake fisheries: an analysis, in Swedish). National Board of Fisheries. Available at: fiskeriverket@fiskeriverket.se

Anon., 2002. EUNIS Habitat classification. European Environment Agency. http://eunis.eea.eu.int/index.jsp

Anon., 2003. A desk-study of diverse methods of fishing when considered in perspective of responsible fishing, and the effect on the ecosystem caused by fishing activity. TemaNord report 2003:501, Nordic Council of Ministers.

Anon., 2004. Marine Life Information Network: Biology and Sensitivity Key Information sub-programme (online). Plymouth: Marine Biological Association of the United Kingdom (cited 08/02/2006) Available from http://www.marlin.ac.uk

Anon., 2006. Effekterna av utflyttad trålgräns på fisk och bottenfauna. Analys av ökad användning av passiva redskap innanför trålgränsen samt de ekonomiska konsekvenserna för näringen (in Swedish). Swedish Board of Fisheries. Available at fiskeriverket@fiskeriverket.se

Ask, L., Westerberg, H., 2006. Fiskbestånd och miljö i hav och sötvatten. Resurs- och miljööversikt 2006 (Fish stocks and environment in marine and fresh waters. Overview over resources and environment 2006, in Swedish). National Board of Fisheries. Available at: fiskeriverket@fiskeriverket.se

Baumann, H., Tillman, A.-M. 2004. The Hitch Hiker´s Guide to LCA. Studentlitteratur, Lund, Sweden.

Berlin, J. 2003. Life Cycle Assessment (LCA): An introduction. *In* Environmentally-friendly food processing. *Edited by* B. Mattsson, Sonesson, U. Woodhead, Cambridge, pp. 5-15.

Catchpole, T.L., Frid, C.L.J., Gray, T.S. Resolving the discard problem- A case study of the English *Nephrops* fishery. Article in press in: Marine Policy (available online at: www.sciencedirect.com).

ESRI 2004. ArcGIS/ArcView/ArcMap version 9.0 Environmental Systems Research Institute, Redlands, California, US.

Evenbratt, H., 2005. QIM (Quality Index Method) assessment of cod and Norway lobster caught by various fishing methods. Student thesis, Chalmers University of Technology, Dep. of Chemical Engineering/Food science, 38pp.

Hauschild, M., Wenzel, H. 1997. Environmental Assessment of Products. Chapman & Hall, London.

ISO, 2002. ISO 14000:2002. Svenska standarder för miljöledning (Swedish standards for environmental management, in Swedish/English), SIS Förlag.

Kelleher, K. 2005. Discards in the world's fisheries. An update. FAO Fisheries Technical Paper 470.131pp.

Nilsson and Ziegler, 2006. Spatial distribution of fishing effort in relation to seafloor habitats of the Kattegat, a GIS analysis. Aquatic Conservation: Marine and Freshwater Ecosystems. Online: DOI: 10.1002/aqc.792

PRé Consultants. 2004. SimaPro Analyst 6.0.4. Amersfoort, the Netherlands.

Thrane, M., 2004*a*. Energy consumption in the Danish fishery.J. Ind. Ecol. **8**: 223-239.

Thrane, M., 2004*b*. Environmental impacts from Danish fish products, hot spots and environmental policies. Doctoral dissertation, Dept. of Development and Planning, Aalborg University, Aalborg.

Thrane, M., 2006. LCA of Danish Fish Products. New methods and insights. Int. J. LCA **11**(1):66-74.

Tyedmers, P.H., 2001. Energy consumed by north Atlantiv fisheries. *In* Fisheries impacts on North Atlantic ecosystems: Catch, effort and national/regional datasets. Fish. Cent. Res. Rep. **9**(3):12-34.

Ulmestrand, M., Valentinsson, D., Sangster, G.I., Bova, D.J., Kynoch, R.J., Breen, M., Graham, G.N., Soldal, A.V., Cruickshank, O., Moth.-Poulsen, T., Lowry, N., 1998. Nephrops survival after escape from commercial fishing gear discarded from deck. In: Report of the study group on Life Histories of Nephrops. ICES CM 1998/G9: 104-110.

Valentinsson, D., 2006. Mandatory use of species-selective grids in the Swedish *Nephrops* trawl fishery on national waters. Experiences after two years. Report. National Board of Fisheries, Institute of Marine Research, Lysekil. (available from daniel.valentinsson@fiskeriverket.se)

Wenzel, H., Hauschild, M., Alting, L., 1997. Environmental Assessment of Products, Chapman & Hall.

Wileman, D.A., Sangster, G.I., Breen, M., Ulmestrand, M., Soldal, A.V., Harris, R.R., 1999. Roundfish and Nephrops survival after escape from commercial fishing gear. EC Contract No FAIR-CT95-0753. Final Report 1999.125pp + app.

Ziegler, F., Hansson, P.-A. 2003. Emissions from fuel combustion in Swedish cod fishery. J. Cl. Prod. **11**: 303-314.

Ziegler, F. and Nilsson P., manuscript. Environmental Life Cycle Assessment (LCA): A new perspective on resource use and environmental impact of fisheries.

Ziegler, F., Nilsson, P., Mattsson, B., Walther, Y. 2003. Life Cycle Assessment of frozen cod fillets including fishery-specific environmental impacts. Int. J. LCA **8**: 39-47.

Ziegler, F., 2006. Environmental Life Cycle Assessment of Norway lobster (*Nephrops norvegicus*) caught along the Swedish west coast by creels, conventional trawls and species-selective trawls. A data report. SIK report 746, SIK, Göteborg, 36 pp (available from SIK library: hr@sik.se).