The Sole Question

Assessing the sustainability of fishing versus farming

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1 Title freely adapted from W.S. Jevons (1865), The Coal Question: An inquiry concerning the progress of the nation, and the probable exhaustion of our coal-mines. Macmillan and Co. London.
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SUMMARY

Fish stocks in the world are declining, but the demand for fish products is increasing. Aquaculture practices are increasing because of this gap between supply and demand. Therefore it is important to determine which production system has the least environmental impact.

In this research the sustainability of two sole production systems for the Netherlands is estimated. The sustainability is defined as a combination of four factors: energy requirements, direct and indirect land use, environmental stressors and ecological impact. Several methodologies are used to calculate the impact. The assessment of the indirect land use is based on the Ecological Footprint method. The environmental stressors are calculated based on a Life Cycle Analysis method. The ecological impact is estimated by using a questionnaire from the North Sea Foundation.

Three factors are combined in a triangular diagram to visualize the overall environmental impact and to compare the two production systems. For all three factors in the diagram; energy requirements, ecosystem support area (or indirect land use) and ecological impact, the fisheries production system has a higher value. That indicates that for sole the aquaculture production is the more sustainable production system.

Both production systems can be improved to reduce their impact on the environment. For fisheries this can be achieved through policy measures. Hereby the fishing intensity will be reduced resulting in a healthier fish stock and less energy needed to catch the same amount of sole. For aquaculture improvements can be achieved by making adaptations in the production system where the most important one is achieving a more efficient water circulation system to reduce the energy requirements.

Although the methodologies being used in this research are not completely sufficiently adequate on their own, in combination they are proper tools to give an overview of different aspects of the sustainability of the two production systems.
1 INTRODUCTION

Fish stocks all over the world are declining. The FAO states that over 70% of all the world fish species are overharvested (FAO, 2004). The progress in fisheries technology and its increasing efficiency resulted in an enormous growth in fish catches from 1950 onwards. Since the nineties, growth in capture fish production levelled off as the maximum production capacity of the world oceans was reached. The total amount of catches remained stable even though the fishing intensity was increased. Global fish production, however, continued to increase due to increased aquaculture production. Fish catches, together with the production of aquaculture need to fulfil the rising demand of fish (FAO, 2004). The consumption of fish is increasing at this very moment. Health institutions like the Heart Foundation, the Nutrition Centre and even the general practitioner claims that fish is a healthy food product and with the current problems of obesitas and related health issues, fish is a good replacement for meat (Klootwijk, 2006). The reasons why fish is said to be healthy is due to Omega-fatty-acids present especially in fat fish like salmon, eel and herring. These fatty-acids are becoming a trend now and consumers believe it is very healthy to consume (more) fish. Together with the health claim of fish, fish consumption is increasing because it has become more luxurious. Fish used to be very abundant and was therefore considered food for the common people. Now it is getting a different image which makes it more desirable to buy fish.

The increasing fish consumption, together with the stagnating catches, creates a gap between the supply and demand of fish products. The breeding of fish can be a possible solution to this problem by increasing the production and therefore bridging the gap. Already most of the salmon currently available in supermarkets originates from aquaculture. Unfortunately both traditional fishing methods and aquaculture generally have negative ecological impacts. For traditional fishing methods like beam trawling or purse seining damage can be inflicted on the marine ecosystem by reducing the standing stock, bycatch of non-target species, or harmful to the benthic community. Most of these impacts are already well studied (FAO, 2004).

The increase in aquaculture has many (possible) negative consequences for the environment as well. Since the technology is still developing and is expanding for several species, not all factors that can be harmful to the marine environment are already known. But one of the negative factors due to aquaculture is the contamination of the natural environment by (over)feeding the fishes and the use of antibiotics. So there is in difference in both methods in how and to what extent they can have an impact on the environment.

Actors in the fish production or consumption, for instance consumers or policy makers, like to know what production system is better for the environment. That is the major driver behind this research. Not only the answer to the question ‘What production system has the least overall environmental impact?’ is important, but also ways to improve the current production system.

1.1 Research aim and questions

This research aims to compare the overall environmental impact of the two production systems. With different methodologies such as Life Cycle Analysis and Ecological Footprint Method the environmental impact of aquaculture on the one hand and wild capture fisheries on the other hand will be measured. Also non-quantitative factors will be taken into account. The main research question is: Which fisheries production system, aquaculture or wild capture, has the least overall environmental impact?

For this project several boundaries are set. It will focus only on one fish species. As a model species the common sole, Solea solea is chosen. Current sole fishing practices are causing a declining sole stock (www.ices.dk/marineworld/fishmap, 2007), which makes it very important to study, especially given the major bycatch problem of the fishing method being used. Aquaculture for sole is starting up, but annual production increases every year. The first deliveries to the market have already been made.
Another project boundary is related to the data. The wild fisheries for sole are dominated by Dutch fishermen who land approximately 80% of the total international landings. Also the only aquaculture business on sole is located in the Netherlands. Therefore it is best to use Dutch data only.

This research addresses the following sub-questions:
- What is the overall environmental impact of aquaculture and traditional fishing practices of sole?
- How sustainable are the different sole production systems? Which factors have contributed the most to the environmental impact?
- How can the existing sole production systems be adapted to become more sustainable?

The term sustainability will be used in this report as a combination of the following factors: energy requirements, environmental stressors, direct land use, ecosystem support area and ecological impact. These factors are further described in section 1.2.

By answering the questions as stated above, conclusions can be drawn about which production system is better for the environment and which factors contribute the most. Also recommendations are given about where improvements are helpful to increase the sustainability.

1.2 The scope of the study

To answer the research questions several methods are used. Since the methods have their limits, more than one are used to obtain an adequate overview of the overall environmental impact of both production systems. The scheme in figure 1 shows an overview of the project and the methodologies that are used for different purposes. For both production systems the same pathways are followed. First the direct and indirect energy use is calculated. Then the environmental impact by using the methodology of the Life Cycle Assessment is estimated. Then the land use and the ecosystem support area (by using the methodology of the Ecological Footprint) is estimated. Finally the ‘traffic light’ method of the North Sea Foundation will be used to value the ecological impact. All methodologies will be further described in chapter 3.

Figure 1 An overview of the research outline.
Subsequently, three outcomes are used in a triangular diagram to visualize the overall environmental impact of both production systems. The following values are used in the diagram; energy use, indirect land use (or ecosystem support area) and the ecological impact (see figure 2). This diagram, together with the LCA outcome are used to compare the two production systems.

Figure 2 Hypothetical outcome of the triangular diagram. The main goal is to visualize the overall environmental impact of the production systems.
This report focuses on the common North Sea sole. The species sole, *Solea solea* belongs to the group of flatfish. Flatfish are species that live at the bottom of the seafloor, where they dig themselves into the sand. It feeds mostly on worms, shellfish and smaller fish. Sole can grow up to 60-70 cm, but most landings of sole are of or just above the minimum landing size of 24 cm (www.ices.dk/marineworld/fishmap, 2007). Small soles are considered a delicacy, but are still juveniles and have not yet had a chance to reproduce. (Klootwijk, 2006)

The North Sea sole is temperature-sensitive, therefore it moves around during the year. During spring time it moves more to the coastline, because of the abundance of food. In the fall it moves further back into the North Sea. During cold winters it moves to deeper places of the North Sea and there it is easier to catch it due to its passive cold-related state. During warmer winters, which have been the trend lately, the sole stays more in the same place. Due to the warmer temperatures the sole remained mostly in the coastal areas during the past couple of years (www.ices.dk/marineworld/fishmap, 2007).

### 2.1 Status

The International Council for the Exploration of the Sea (ICES) states in its yearly advice of 2005 that, based on estimations of fishing mortality and the standing stock biomass, the stock of the North Sea sole has a full reproductive capacity and that it is harvested in a sustainable manner. In 2004 the spawning stock biomass was estimated at 42 000 tonnes (see figure 3), just above the minimum required level (precautionary biomass) of 35 000 tonnes (ICES, 2005). In 2004 the fishing mortality was 0.35 which was at or near the precautionary limit. Fishing mortality is an indicator for the fishing intensity on a fish stock. Policy measures to improve the status of the sole are aimed at reducing it to 0.2 (ICES, 2005).

![Figure 3 A schematic representation of the spawning stock biomass of the North Sea sole in tonnes. (ICES, 2005)](image-url)
Thus at this point the stock size is just above safe biological limits, but the overall status is not healthy, according to fisheries biologists and the North Sea Foundation (www.noordzee.nl/visserij, 2007). The stock of a fish species is considered to be healthy when it is composed of multiple age groups. The landing data for sole indicates that it consists mostly of juvenile fish, which indicates an unhealthy stock. Most catches contain predominantly juvenile species because of the high fishing pressure. This results in catches of juvenile, mostly undersized, sole. It is striking to note that nowadays the sole reaches its maturity at an earlier age than about 20 years ago. Due to fishing pressure the sole matures earlier in life, but one may assume that this spawn is of lower quality than that of older individuals (www.noordzee.nl/visserij, 2007). This can result in a lower recruitment rate of sole. Figure 4 shows the recruitment of the past 50 years. It fluctuated a lot over the years, but in the past years high peaks are lacking. This shows no real reason for concern, even though it is assumed that the quality of the spawn is reducing.

![Figure 4 Recruitment of the North Sea sole over the past 50 years. (ICES, 2005)](image)

Finally there is another factor that has an effect on the status of sole. Fisheries biologists are concerned about the status due to the reducing amount of good age groups. Apparently they fluctuate in quality and lately there have only been good years in 1996 and 2001. Therefore the prospect for sole is not good according to fisheries biologists. (www.noordzee.nl/visserij, 2007; Rijnsdorp, 2007)
2.2 Fisheries production system

Sole is an important species for the Dutch fishing fleet. Six countries are involved in fishing activities on sole in the North Sea; Belgium, Denmark, England, Germany, France and the Netherlands. The last one has the largest share of 69% of the total fleet. The Dutch fleet uses beam trawlers while fishing for flatfish. Figure 5 shows a picture of a beam trawl. Beam trawling is an effective way for fishing for flatfish. The beam trawl is being dragged over the bottom of the seafloor. The chains that are attached (see figure 5) will scare the fish out of the sand, which are then being caught in the net. The total weight of the beam trawl is over 7000 kg. (www.noordzee.nl/visserij, 2007) Another way to fish for flatfish like sole is to use a passive fishing method like standing nets, which are used by Danish fishermen.

Figure 5 Picture of a beam trawl used for sole and plaice fishing. (www.marlab.ac.uk 2007)

The minimum mesh size for all demersal trawls is set at 100 mm, although the fishery for sole is allowed to use a minimum mesh size of 80 mm south of 55 degrees northern latitude. These measures were taken to reduce the capture of undersized fish. Although the bycatch of undersized sole in an 80 mm beam trawl are small, large amounts of undersized fish of other species are being caught, in particular dab and plaice.

The landings of the North Sea sole are given in figure 6. The data are from the six countries combined. The landings over the past 50 years are fluctuating, but overall they are not decreasing or increasing. The landings of sole of the Dutch fleet for the last 5 years are around 13 000 ton. (ICES, 2005)

Figure 6 The total landings of sole in the North Sea area in the period 1957-2005. (ICES, 2005)

Even though landings overall have been stable, the fishing effort has increased. In the sixties the average engine power of the fleet was around 300 horsepower (hp), but has increased ever since. In 1987 the maximum engine power was set at 2000 hp, and ships exceeding this engine power were allowed to continue fishing, although they were only allowed to replace the vessel or engine with the maximum 2000 hp.
The major adverse consequences of the fishing for sole in the North Sea are due to the method being used. Beam trawling damages the sea floor and benthic species living on or in the upper layer of the sea bed (Jennings & Kaiser, 1998; Piet et al., 2000). Bycatch is also a major issue of the fishing for sole. The biggest problem of bycatch is the capture of undersized fish. The problem relates to the fact that sole and plaice are being fished for at the same time and location. There are of course variations in the abundance of both species, but the Dutch fleet for flatfish is fishing for sole and plaice simultaneously. In general the sole fishery with their 80 mm mesh size captures many undersized plaice, but the other way around is not as common (Rijnsdorp, 2007). These negative ecological effects, together with the fact that the stock is being reduced by fisheries, indicate that the current sole fisheries is not a perfect method.

2.3 Aquaculture production system
Aquaculture is the fastest growing food producing sector in the world (FAO, 2004). For sole there have been only limited pilots and small-scale production in aquaculture. Solea BV is located in IJmuiden, the Netherlands, where since 2001 sole is being bred in captivity for large scale production. At this point the annual production is about 33 tonnes of sole, but plans are to expand it to 100 tonnes (Kamstra, 2007).

The production system is a closed recirculation system, where the soles are being kept in so called shallow raceways. These are 50 meters long basins, stacked on top of each other. In total there are 28 raceways for the current production of 33 ton. The water is being circulated through these basins by one pump, and filtered through a biological filter to remove the residues. For oxygen supply liquid oxygen is added to the water. The optimal temperature for the fishes is about 20 degrees Celsius. In order to maintain this temperature the water sometimes has to be heated, but most of the time it is necessary to cool it due to the metabolic processes of the fishes (Kamstra, 2007).

Figure 7 Multiple soles in a raceway at Solea BV
The aquaculture of Solea BV is unique because of its own breeding stock. The production system is almost completely independent from the natural system. The whole process of the reproduction is quite complex and the details are not discussed here. But it is important to mention that on an annual basis, only about 100 individuals are taken from the wild. A major advantage from the breeding stock is that Solea BV can deliver to the market at all times during the year, instead of seasonal fluctuations in the wild (IMARES, 2004). Another very important process is the feeding of the fish. Before entering the big raceways the fish weighs about 7 gram. When they are ready to be shipped to the market their weight is approximately 300 gram. It takes about 1.5 years to gain this weight. The total amount of distributed fish-food is on average 175 kg a day, but it varies with the size of the fishes present in the system. They are fed with pellets made for the feeding of Danish turbot. The food contains about 10% fish oil, which turned out to be important for the digestion of the food. Apparently sole is very sensitive to its type of food, it is favourable that the food contains the least amount of fish oil as possible (Kamstra, 2007). Even though the fish are fed with other types of food than the wild stock (normally they eat worms, small fishes and shellfish), a TNO research shows that there is no difference in taste for sole of Solea BV compared to wild captured sole(IMARES, 2004). This is of course essential for the viability of the company.

Since Solea BV is still developing it is hard to describe the negative ecological effects of its current production method. One may presume that the residues from the biological filter can give rise to a pressure on the ecosystem, but these residues are used as a fertilizer. The drain off of waste water is also likely to give negative effects, but since it is a closed recirculation system, this amount is negligible. The only process that is likely to cause negative ecological effects is the feeding of the fish. In order to maintain the fish in the raceways for 1.5 years, many small pelagic fish are being captured and processed into fish-feed for the sole. This is further described in section 3.3.
3 METHODOLOGY

Different methods can be used to estimate the overall environmental impact of fish production. For this research the methods are separated in two categories. The first methodology includes quantitative factors, which makes it possible to express the environmental impact in a simple number. The other category deals with non quantitative factors. In this section the methodology which is being developed and used by a Dutch NGO, the North Sea Foundation is described. Also two types of certification for fish products will be described.

3.1 Quantitative methodology

For this research different methodologies are used to quantify the environmental impact of sole production. The methods are derived from environmental science. The concepts of the methodologies are used to calculate the overall environmental impact.

3.1.1 Ecological Fishprint

The ecological fishprint is derived from the well known methodology of the ecological footprint. An ecological footprint is defined as follows by Wackernagel and Rees (Wackernagel & Rees, 1996): “The ecological footprint is a measure of the “load” imposed by a given population on nature. It represents the land area necessary to sustain current levels of resource consumption and waste discharge by that population.”

The original ecological footprint concept does not incorporate the marine world into the calculations. The reasons for this are; 1) the marine area contributes only for a small part to the entire human consumption, 2) it is already known that marine ecosystems are overexploited, 3) management is more based on terrestrial world than on the marine world, 4) incorporation of the marine area is not necessary to state that human are exceeding the carrying capacity of the world (Wackernagel & Rees, 1996).

These four arguments to exclude the marine world from the ecological footprint stems from a biased to a terrestrial point of view and is not a legitimate argument since marine ecosystems are heavily impacted by human activities and there is serious concern for the sustainability of the exploitation. For management it can thus be necessary to include the marine part of the ecological footprint. The ecological fishprint may help to achieve this goal.

Ecological fishprint (further referred as EF), similar to the ecological footprint, is a method to describe whether or not fisheries is a sustainable practice. It estimates the area that is required for aquaculture or fisheries. Hereby taken into account the inputs, like the ecosystem area for producing the fish-food in aquaculture, and outputs, like the amount of fish being produced (Wołowicz, 2005). The outcome gives a measure about the capacity of the seafood production system.

As mentioned in section 2.3, there are many possible environmental impacts to aquaculture. The only factor lacking in the literature is the magnitude of these impacts. Here the EF can also be of assistance. This accounts for the wild fisheries as well, although their impacts are not as numerous.

There are many different ways to calculate the EF. Wołowicz (Wołowicz, 2005) mentions three different methods; 1) spatial ecosystem fishprinting, where an estimate is made of the ecosystem support area which is necessary for the total inputs and outputs of the production system; 2) spatial to weight fishprinting calculates the ecosystem system support area per kg of fish; 3) weight to spatial area fishprinting, where the amount of weight of fish is converted into an area needed as an ecosystem support (Wołowicz, 2005). In this research the method of spatial to weight fishprinting will used as this method is the most applicable and inclusive fishprint method (Wołowicz, 2005). Also this methodology has been used extensively by Tyedmers in his dissertation on the sustainability of salmon (Tyedmers, 2000). Data from this report are being used as a comparison for the sole data. Finally, in this type of EF the calculation in kg of fish can be directly related to amount of fish produced or sold per year.
Another type of method is the one from the Sea Around Us Project from the University of British Colombia, which uses an equation to express the EF as a value of the necessary primary production related to the trophic level of the fish species (www.seaaroundus.org, 2007). When it exceeds the Exclusive Economic Zone of the country, it can be accounted for as not sustainable. This calculation is an easy and straightforward process, but therefore also in many ways very limited.

Data from the literature (Folke et al., 1998; Kautsky et al., 1997; Larsson et al., 1994; Warren-Rhodes et al., 2003) show evidence of unsustainable fishing practices regarding the ecosystem support area. Outcome of ecological fishprints varies from almost nothing to 50000 times the area of activity (Folke et al., 1998). The fishprints tends to be much larger for carnivorous species, such as salmon, than for herbivorous and omnivorous species. A striking difference is that the total amount of energy needed to breed tilapia in intensive cage farming is 1.5 times higher than for semi-intensive pond farming on tilapia in Zimbabwe (Berg et al., 1996). Thus it matters, at least for this species, how they are being produced. Another outcome of research on EF is the fact that for produced salmon the impact on the supporting ecosystem was the same for fish being farmed in cages, ranched at the coast or captured in the wild (Folke, 1988). An important conclusion from these data is that ecological fishprints are very species specific, i.e. an EF of salmon is very different from an EF of shrimps.

Of course there are limits to the use of ecological fishprint as a method for quantifying environmental impacts. The major constraint is that not all environmental factors can be quantified. Factors such as genetic impacts, chemicals and antibiotics discharge, and effects on other wildlife are therefore not included in the fishprint (Wolowicz, 2005).

### 3.1.2 Life Cycle Assessment

The methodology of Life Cycle Assessment (LCA) is well-known in the field of environmental sciences to estimate the overall environmental impact of a product along its entire life path, ‘from the cradle to the grave’. The product is evaluated by analysing the environmental impact of the materials and processes during the three different life stages (production, use and waste phase).

Originally LCA was developed for land-based industrial products. However, in recent years LCA has been applied to fish and fish products (Ellingsen & Aanonsen, 2006; Hospido & Tyedmers, 2005; Papatryphon et al., 2004; Thrane, 2006; Ziegler et al., 2003), but it is agreed upon that the methodology still needs improvements in relation to fish products, e.g. better adapted environmental indicators (Ellingsen & Aanonsen, 2006).
Figure 8a Outcome of a LCA on wild caught cod (Ellingsen & Aanondsen, 2006). The environmental impact is indicated in eco-indicator points per functional unit of a 200 g fillet.

Figure 8b Outcome of a LCA on farmed salmon (Ellingsen & Aanondsen, 2006). The environmental impact is indicated in eco-indicator points per functional unit of a 200 g fillet.

Data of LCA on fish show that the fishing and farming stage are the phases that are giving rise to the most environmental impact, see figure 8a and 8b (Ellingsen & Aanondsen, 2006). This supports the choice of systems boundaries in section 3.3 of leaving out processes after landing and focus on the most important processes.
3.1.3 Energy Analysis Program

The Energy Analysis Program (EAP) is used as a database for several processes in both production systems. EAP is a computer program developed by IVEM to determine the life-cycle energy use of a product of consumptive expenditure. The direct and indirect energy use of a product is calculated by process analysis and input-output analysis (Wilting et al., 1999).

3.2 Non quantitative methodology

Nowadays there are already methods being used to value the degree sustainability to specific fish species. For labelling fish products different non quantitative methods are being used. First, such a methodology, which is being used by the North Sea Foundation, is described. The main advantage for this type of methodology is that they include factors that cannot be quantified by the Ecological Fishprint and the Life Cycle Assessment. Then certification procedures by two different institutes which are responsible for the certification of fish products.

3.2.1 North Sea Foundation methodology

The North Sea Foundation is a Dutch NGO aiming at ‘a clean and healthy sea for humans and animals’. They published, together with Wouter Klootwijk a consumer guide with an indication on which fish to leave alone and which fish you can buy with a good conscience (Klootwijk, 2006). Indication is given by using a ‘traffic light symbol’, green for ‘good’ fish, red for those doing badly, and yellow for the one in the middle. The indication is based on a questionnaire which focuses on three aspects of the production system. For fisheries these are the biological aspects of the stock, the ecological effects of the fisheries and the relevant policies. For aquaculture the three aspects are the production system and feeding, the ecological effects on the environment and the relevant policies. Questions focus on wild stock, fisheries pressure, discards, waste discharge etc. The complete questionnaire is described in the appendix A1.

By answering the questions the fish species are valuated by a score. The boundaries are set as follows; dark green 80-100%, light green 60-80%, orange 40-60%, light red 20-40% and dark red 0-20%. This indicates the status of the species.

The North Sea Foundation methodology focuses on the ecological aspects of the production system, and not so much on the environmental aspects. In that way this methodology can complement the methods described in section 3.1.

3.2.2 Certification

In the Netherlands there are some fish species certified as ‘sustainable’. Institutes which are involved in this certification are for instance the Marine Stewardship Council (MSC) and SMK (Stichting Milieukeur). The MSC only certifies wild fisheries products and works with a methodology similar to that of the North Sea Foundation. The MSC evaluates the species based on three principles; status of the stock, ecological effects and policies. The SMK is a Dutch institute working on the certification of multiple food and non-food products. For aquaculture products in the Netherlands this is the institute to certify fish products as sustainable. However, the method of SMK is currently too limited for this purpose.
3.3 Research system boundaries

This research focuses on the environmental impact of the two production systems as described above. For the analysis it is important to only take into account processes in which both production systems differ from each other. The point at where both systems become similar is at the moment of landing. Hereafter they are delivered to the market and are transported and processed in a similar way. Thus fishes from the wild and from Solea BV are handled in the same way after landing. Another argument for leaving out processes after landing is because they relatively do not add much more energy to the total energy requirement of the whole production system (Moll, 2007).

Empirical evidence, presented in the previous sections, shows that most of the impact of the two production systems is in the phase of the actual fishing and farming. Therefore the focus of this research will be on these two phases. Hereby keeping in mind the Pareto principle, or ‘80-20 rule’, which states that generally 80% of the results is caused by 20% of the causes. This does not mean that other factors can be left out, but the focus will be on the major issues. Furthermore, for the comparison which will be made between the aquaculture production system and the wild capture fisheries, it is not necessary to concentrate as much on the whole production system ‘from the cradle to the grave’. It is assumed that analysing the fishing and farming phase will be sufficient for answering the research question.

The argumentation for the system boundaries for both production systems is as follows.

For both production systems the capital goods are not taken into account. For fisheries the ships are left out of the analyses because ships have a very long life span. For the period of 2001 to 2005 over 40% of the ships of the Dutch fishing fleet for flatfish are older than 20 years (calculated from (Taal et al., 2006)). This probably accounts for the raceways of Solea BV as well. These solid constructions are made of steel and other long life-span materials. Even though they were recently built and at this moment are being expanded. It is expected that they will last for a long period. Therefore both the ships and raceways are left out of the analysis. For both aquaculture and fisheries labour input is left out as well. It is assumed that the staff employed is not consuming (much) more energy while working than if they were at home (Moll, 2007).
The production system for fisheries is fairly straightforward. Figure 9 gives a schematic overview of all the processes. The most important processes are navigating and catching, which are the basics of fishing for sole. To keep these processes going two other processes are necessary: maintenance of fishing tools and the burning of fossil fuels. The burning of fossil fuels is a very important energy user. The influence of maintenance depends on the frequency with which it takes place, but for fisheries the maintenance of the ships and fishing gear adds a fair amount to the overall energy requirement. Another important process for the fisheries is cooling. After catching the fish, they are being cooled on board on ice chips, which are produced by cooling systems on board.

Figure 9 Schematic overview of the processes involved in sole fisheries. Boxes indicated with a striped line are not considered for the quantitative analysis, a solid line indicates the processes included in the analysis and the boxes with a thick solid line are considered the most important processes. The line that separates the processes of cooling and landing indicates that landing is not taken into account in the analysis.
For the aquaculture production system the overview of processes is more complex than wild capture fisheries (see figure 10 for an overview). This results from the fact that processes which normally take place in the sea are now incorporated in the production system. In aquaculture the most important processes are the overall water treatment, the actual breeding of the fish and the capturing of fish for fish-food. The water treatment consists of four processes which are all taken into account in the analysis because they are important for the continuation of the system. The four processes are the water purification by a biological filter, the cooling or heating of the water, the water circulation by a central pumping system and the addition of liquid oxygen.

Figure 10 Schematic overview of the processes involved in sole aquaculture. Boxes indicated with a striped line are not considered for the quantitative analysis, a solid line indicates the processes included in the analysis and the boxes with a thick solid line are considered the most important processes. The line that separates the processes of cooling and landing indicates that landing is not taken into account in the analysis.
For feeding of the fishes in the raceways fish-food is needed. For this purpose small pelagic fish species like herring, anchovies, sardines and sandeels are caught. The origin varies widely from Scandinavian or South-American countries like Norway and Peru. The transport by boat from both regions is taken into account. The capturing of the small fish is mainly done by purse seining. This method uses large ringnets, which are being closed around the school of fish. It is a very effective fishing method for catching pelagic fish (see figure 11).

![Figure 11](www.ejfoundation.org/printpage271.html, 2007)

These catches are then processed into fish oil and fish meal. Since data about the fish-food for Solea BV are not available, estimations of the direct energy requirements of comparable practices are made. Indirect requirements of these processes, i.e. packaging of fish-food, maintenance of ships for capturing or transporting etc. are left out of the analysis, because these processes are not directly related to this production system.

These system boundaries for both production systems are conditional. During the analysis other additional processes may come up or processes may appear to be negligible compared to other processes. In the discussion the system boundaries are to be put forward again and the argumentation, as stated here, are debated.
4 DATA ANALYSIS

4.1 Origin of data
Data for the analysis were derived from the Dutch research institute LEI (Taal et al., 2006), the sole aquaculture company Solea BV, the Energy Analysis Program from the Center for Energy and Environmental Studies IVEM (Wilting et al., 1999), the company which supplies oxygen to Solea BV: Air Products BV, the Food and Agriculture Organisation of the UN (FAO, 1984), and a PhD thesis (Tyedmers, 2000). As a reference period for wild fisheries the period 2001-2005 is chosen. Selecting the most recent 5-year period will level off fluctuations and represents the current fishing practices. For aquaculture the reference period is one year only (half way 2005 to half way 2006), because Solea BV is rapidly developing every single year which makes the production system more efficient. Therefore only the most recent data were used.

4.2 Allocation
For fisheries there is the question of allocating energy use to the different components of the catch, since beam trawling takes place simultaneously for multiple species (Daan, 1997). So one can not exactly indicate how much energy is used on sole only. The total amount of catches can be allocated for sole based on the economic value or on the proportion to the total landed weight (mass allocation). Both methods are used in the analysis. The mass allocation is in line with the consumption and the quota, but the economic allocation gives a better view on the economic importance of sole, which has a much higher market value than for instance plaice (Taal et al., 2006).

4.3 Energy requirements
First, for both production systems the direct and indirect energy requirements were calculated. The energy needed to continue the system processes which are directly related to the end product is estimated. The energy carriers are diesel, gas and electricity. For fisheries the total energy requirement is the sum of the fuel used during navigating and catching (Taal et al., 2006), and the energy requirements for maintenance (Wilting et al., 1999) per kg of produced sole. For aquaculture the estimated direct and indirect energy requirement is the accumulated energy from the electricity and gas use from the company (Solea BV), the fuel use for catching fish for fish-food (Tyedmers 2000), the electricity and gas use for the fish food production (FAO, 1984), the energy to produce liquid oxygen (Air Products BV), and the energy to transport the fish-food overseas and to transport the liquid oxygen by road transport in the Netherlands (Taal et al., 2006) per kg of produced sole.

Several assumptions were made for this analysis. For fisheries the only assumption was about maintenance. There were only data available about the total technical costs, which include maintenance. A share of 42% of these costs was assigned to oil costs (Taal et al., 2006). So 58% of all technical costs were assumed to be for maintenance. The conversion from these costs to energy requirements was made with EAP data (Wilting et al., 1999); construction and reparation of ships, drilling platforms etc. This category seemed to be the most relevant category for the maintenance of the fishing fleet (Wilting et al., 1999).
Multiple assumptions were made concerning the aquaculture production system. Since the production company for fish-food was not able to deliver data, most assumptions are made for the processes related to fish-food. First, the exact origin of the fish for the fish-food is unknown, but it is known that it is either from Scandinavia or from South America. Two countries, Norway and Peru, are chosen as examples, because they are well-known for their major fishing industries. The species that are being fished for are small pelagic species, such as herring, sandeels and sardines. The most common fishing technique for such species is purse seining, which is essentially a method whereby a huge net is encircled around a school and closed from beneath. Since data were available on the energy requirements for purse seining on herring in British Colombia, Canada, these data were used for this analysis (Tyedmers, 2000). For salmon the conversion ratio from the pelagic fish (wet weight) to the fish-food pellets (dry weight) ranges between 3.1 and 3.9 (Tacon, 2005), where the fish contents are around 30% of the dry feed. Since the fish-food that is being used by Solea BV contains over 85% of fish products, the assumption is made that 5 kg of caught fish is sufficient for 1 kg of fish-food, hereby leaving out the by-products of 15% of the food. Since no data are available on the three foreign countries that are incorporated in the analysis, Dutch data from EAP are used instead. Another assumption on fish-food is on the fuel use to produce fish meal and oil. The FAO does not provide information about the nature of the fuel, but it is likely to be diesel fuel. Therefore Dutch conversion rates for energy are being used (Wilting et al., 1999).

Finally in the analysis we use distances based on the shortest possible routes between the Netherlands and Norway and Peru.

4.4 Environmental stressors

Since most data are expressed in the amount of energy needed for the production process and transport, a LCA does not provide additional information on the environmental impact. For measuring the environmental stressors of both production systems data from EAP are being used, which include several parameters such as the emissions of gasses (CO\textsubscript{2}, CH\textsubscript{4}, SO\textsubscript{x} and NO\textsubscript{x}), small particulate matter (PM10) and the direct land use. The direct land use of these EAP data are further applied in the land use analysis.

The same production processes as used in the energy analysis are included in this analysis. For fisheries the average data of the reference period are used and taking into account the economic allocation. This is chosen because it represents the economic value of the fish and it shows that the fishermen are willing to use more energy on this species than on others. For the aquaculture data the transport of fish-food is assumed to originate from Peru, because this is a well-known country which produces fish-food.

4.5 Direct and indirect land use

The land use of the two production systems is a parameter of the overall environmental impact, similar to the energy requirements. For the direct land use the EAP data are used, but for the indirect land use an analysis derived from the Ecological Fishprint method is being used. In the indirect land use analysis the ecosystem support area is estimated. It is the global forest ecosystem which is required to assimilate the CO\textsubscript{2} emissions which result from the electricity and fossil fuel inputs. The amount of CO\textsubscript{2} uptake by forests depends on natural factors such as the location, species composition and the age of the forests (Tyedmers 2000). Here it is assumed that the CO\textsubscript{2} emissions are released into the atmosphere. Therefore the global estimated rate of Wackernagel and Rees (Wackernagel & Rees, 1996) of 1.8 tonnes C per ha per year will be used. The total CO\textsubscript{2} emissions for both production system inputs originate from the EAP database. The ecosystem support area is calculated as the area required per kg of produced sole.

The data being used are the same as used for the environmental impact analysis.
4.6 Ecological impact

The questionnaire from the North Sea Foundation for estimating the ecological impact is used. This method is currently being reviewed by the organisation, which we used. But the former questionnaire, which focuses on three aspects per production system, is stated in appendix A1. The valuation of the questions is confidential information, but it was communicated to us on a confidential basis. For fisheries a total of 13 questions were answered, for aquaculture 18 questions in total were answered. By answering each question a score was given to each production system. Depending on the score the production system for sole was valued green, light green, orange, light red or red. Hereby red is an indication for unsustainable practices and green for sustainable practices.

4.7 Integrated view

The integrated view is combining the outcome of the energy requirements, the land use and the ecological impact analysis in a triangular diagram, as shown in figure 2 in chapter 1. From the two production system for the energy requirements and the land use the highest outcome is set at 100%, the outcome of the other production system is a share of that. For the ecological impact the outcome is also given in a percentage. It is given as a share of the range of possible outcomes of the questionnaire. By doing so, the three different outcomes can be compared.

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2 The North Sea Foundation is at this moment reviewing the methodology in cooperation with other NGO’s. Therefore it was not possible to be transparent in the questionnaire and the weighing of the outcome.
5 RESULTS

5.1 Energy requirements

The energy requirements for 1 kg of produced wild captured sole in the Netherlands are given in table 1. With mass allocation the average over five years is 140 ± 8 MJ per kg of sole. The average for economic allocation in the same time period is 405 ± 19 MJ per kg of sole. The energy requirement for maintenance is a share of about 10 percent of the total amount. The variation over the years is small, but it is striking to notice that the fuel use per kg of sole is decreasing over the years, especially for mass allocation. This is due to the increasing share of kg of sole of the total landings for beam trawling.

Table 1 The energy requirements for 1 kg of sole produced by fisheries over the period 2001-2005. There is a separation between mass allocation and economic allocation of the share of sole in the total beam trawl landings.

<table>
<thead>
<tr>
<th>Energy requirements (MJ/kg)</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>average</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mass allocation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel use</td>
<td>135</td>
<td>134</td>
<td>130</td>
<td>118</td>
<td>114</td>
<td>126</td>
</tr>
<tr>
<td>Maintenance</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>13</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>Total</td>
<td>149</td>
<td>147</td>
<td>144</td>
<td>131</td>
<td>129</td>
<td>140</td>
</tr>
<tr>
<td><strong>Economic allocation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel use</td>
<td>353</td>
<td>394</td>
<td>358</td>
<td>346</td>
<td>375</td>
<td>365</td>
</tr>
<tr>
<td>Maintenance</td>
<td>37</td>
<td>40</td>
<td>38</td>
<td>38</td>
<td>47</td>
<td>40</td>
</tr>
<tr>
<td>Total</td>
<td>390</td>
<td>434</td>
<td>396</td>
<td>384</td>
<td>421</td>
<td>405</td>
</tr>
</tbody>
</table>

For aquaculture the energy requirement for the year 2005-2006 is 218 MJ per kg of produced sole. The largest fraction is the electricity from the company itself, due to the major energy requirement for the circulation of water in the raceways. The second largest factor of the energy requirement is assigned to the fuel use for catching herring by purse seining for the fish-food. Together with the fuel use for the food production, these three factors are accountable for almost 95% of the total amount. All other factors are almost negligible in the outcome. Of the energy requirement 75% is accounted for operational processes of Solea BV, and 24% for feeding the fish. The remaining 1% is for other processes, like transport and producing oxygen.

Table 2 The energy requirements for 1 kg of sole produced by aquaculture over one year. For the origin of the fish-food Peru is taken as an example.

<table>
<thead>
<tr>
<th>Energy requirements (MJ/kg)</th>
<th>2005-2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>154</td>
</tr>
<tr>
<td>Gas</td>
<td>10</td>
</tr>
<tr>
<td>Electricity food production</td>
<td>2</td>
</tr>
<tr>
<td>Fuel use food production</td>
<td>13</td>
</tr>
<tr>
<td>Electricity liquid oxygen</td>
<td>2</td>
</tr>
<tr>
<td>Fuel use purse seine fish-food</td>
<td>37</td>
</tr>
<tr>
<td>Transport fish-food (Peru)</td>
<td>0</td>
</tr>
<tr>
<td>Transport oxygen</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>218</td>
</tr>
</tbody>
</table>

The complete dataset for both systems is provided in appendix A2 and A3.
5.2 Environmental stressors

An overview of six environmental stressors of the two production systems is given in table 3. CO₂ and CH₄ are greenhouse gases and these emissions contribute to global warming. SOₓ and NOₓ are indicators for acidification processes. VOC (volatile organic compounds) and PM10 (small particulate matter) contribute to air pollution. The fisheries production system has a higher outcome for CO₂, NOₓ, VOC and PM10. For the stressors CH₄ and SOₓ aquaculture contributes more per kg of produced fish. Large differences are noticeable for CH₄, NOₓ and VOC. The high electricity use in the aquaculture production system results in more emission of CH₄. The high contribution of diesel fuel burning for fisheries leads to a higher share of NOₓ and VOC.

Table 2 An overview of six environmental stressors caused by producing 1 kg of sole in two production systems. The outcomes are in kg for CO₂ and the other stressors in grams.

<table>
<thead>
<tr>
<th></th>
<th>CO₂</th>
<th>CH₄</th>
<th>SOₓ</th>
<th>NOₓ</th>
<th>VOC</th>
<th>PM10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fisheries</td>
<td>27.7</td>
<td>1.7</td>
<td>10.7</td>
<td>80.1</td>
<td>97.6</td>
<td>13.9</td>
</tr>
<tr>
<td>Aquaculture</td>
<td>16.7</td>
<td>12.3</td>
<td>17.8</td>
<td>30.1</td>
<td>15.7</td>
<td>10.1</td>
</tr>
</tbody>
</table>

The complete dataset of the ten environmental stressors per production system are given in appendix A4.

5.3 Direct and indirect land use

The direct land use appeared to be very small for both production systems, for fisheries this is only 0.28 m² and for aquaculture this is virtually zero. The indirect land use, the estimated ecosystem support area for the CO₂ emission from the energy use, has a larger outcome. For fisheries the area is 42 m² per 1 kg of sole. For 1 kg of sole bred in captivity the estimated indirect land use is 25 m². The difference between these two outcomes results from the larger amount of CO₂ emission during fishing practices.

5.4 Ecological impact

The ecological impact for sole fisheries is much higher than for sole aquaculture. Fisheries is valued as red, the aquaculture production system of Solea BV received the color indication light green. The sole fisheries production system receives a bad score and is assumed to be unsustainable due to the high discard rate and the ecosystem effects by the beam trawl method. The causes for the positive outcome for sole aquaculture are various. There is no chance of escapes and disease transfer due to the closed circulation system. Solea BV does not rely on fresh water supply and does not produce discharges harmful to the aquatic environment. The production system does not rely on individuals from the wild and no physical harm is done to the fishes. The only reason why it is not valued green instead of light green is that the production system relies on unsustainably produced fish-food, according to the ‘traffic light’ method.
5.5  Integrated view

The integrated view results in a triangular diagram that visualizes the environmental impact of the production system for three categories; energy requirements, ecosystem support area and ecological impact (see figure 12 and 13). The fisheries production system has a higher impact for all three categories. This is shown by a larger surface area of the triangle. The triangular diagram for the aquaculture production system is much smaller, which visualizes a lower environmental impact of sole if it is bred in captivity.

![Fisheries](image1)

Figure 12 Triangular diagram of the overall environmental impact of the fisheries production system for sole. The ecological impact is an outcome of a questionnaire. The other two categories are percentages of an actual value, where the highest of both systems is set at 100%.

![Aquaculture](image2)

Figure 13 Triangular diagram of the overall environmental impact of the fisheries production system for sole. The ecological impact is an outcome of a questionnaire. The other two categories are percentages of an actual value, where the highest of both systems is set at 100%.
6 DISCUSSION & CONCLUSIONS

6.1 Research questions
The research focuses on the overall environmental impact of two sole production systems. The following three research questions were addressed in the introduction:
- What is the overall environmental impact of aquaculture and traditional fishing practices of sole?
- How sustainable are the different sole production systems? Which factors have contributed the most to the environmental damage?
- How can the existing sole production systems be adapted to become more sustainable?
The first question is answered in chapter 5 where the results of the research are presented. The environmental impact is given as a combination of four factors; energy requirements, environmental stressors, direct and indirect land use and ecological impact. These four factors together are defined as the degree of sustainability of the production system. The second question regarding the sustainability is answered in section 6.4 where the conclusions are presented. The final question is addressed in 7.1 where recommendations regarding sole fisheries and sole aquaculture are given. In the same section a best case scenario for both production systems is presented.

6.2 Uncertainty, validity and sensitivity
For this research several data from different sources are used. The accuracy of these data varies. Even though rough data often has been used, overall it is assumed that it provides a realistic overview of the environmental impact.
For the aquaculture only the data of one company, Solea BV is used. Therefore the outcome of the analysis could have been different. As for the key parameters of the energy analysis (electricity, fuel for fish-food and producing fish-food) the range of possible outcomes cannot be provided, because only data from one company and from one year is used for the analysis.

The outcome of the research is based on several assumptions which influence the validity. Only the major aspects will be discussed here. The building of ships and raceways are left out of the analysis. Including these would have shown higher impacts for both systems. One may assume that the fisheries impact would increase more because building ships involves more energy and materials than building raceways, which are mostly made up from secondhand material. The fish-food analysis considers several assumptions. Even though it is not known which species is being caught for the fish-food, one may assume that this is causing ecological impacts. Especially when keeping in mind that more than 70% of the world fish stocks are overfished (FAO, 2004). In the calculations the conversion of 5 kg fish into 1 kg fish-food is an estimation based on the literature. The conversion could also have been higher for the fish-food being used by Solea BV. In that case the overall environmental impact for aquaculture would have been higher.
For Solea BV the reproduction phase of the sole is not included in the analysis, because then only the actual farming process would be estimated. But data show that the reproduction phase also requires energy. Formaline that Solea BV uses for water purification is excluded from the analysis. But it is not extensively used and it will not contribute significantly to the total energy requirement, similar to the liquid oxygen. The waste of the biological filter on the aquaculture production system is completely converted into fertilizers and therefore will not contribute significantly to the overall environmental impact.
Dutch conversion factors for energy are used for the foreign production of fish-food and catching the pelagic species. This gives a skewed view, because the energy use in the foreign countries is not analyzed. For more thorough analysis this should be taken into account. But for this explorative type of research it was considered sufficient.
The time period taken into account for the aquaculture production system is only one year. This makes the outcome rather uncertain. But the production of Solea BV is becoming more efficient because of improvements. Therefore it is reasonable to assume that the range of outcomes could not have been much higher. For the fisheries a time period of five years was chosen. The fuel use over the last 20 years has been fluctuating, but stayed in a similar range. But the energy requirements for sole depends also on the availability of good age groups. In the chosen reference period of 2001-2005 these are lacking, which can imply to a higher energy use per kg of sole compared to earlier time periods. Even though it can be assumed that this period provides a representative view of the energy use for sole fisheries.

Different methodologies were used for the analysis. The most important aspects of these methods will be discussed here. The ecological footprint is a very rough estimate for the ecosystem support area. The EF is a practical indicator for sustainability, but not completely without flaws and fully accurate (Roth et al., 2000). Although it is a good visualization tool, it is not an effective method to compare production systems and to provide (policy) recommendations (Bunting, 2001). So it can be used to present an overview of how the production system indirect effect the ecosystem, but it is better to focus on the direct ecological impacts and emphasize these.

Although only the basic elements of the LCA methodology has been used in this research, a complete LCA can be a very good methodology to asses a more extensive environmental impact analysis. For the environmental stressors analysis the data from the energy requirements were used. By performing an LCA the environmental stressors from other processes except energy use can be analyzed.

The 'traffic light' method was a valuable method for assessing the ecological impact, but the weighing of the answers to the questionnaire is open to discussion. It is very difficult to compare certain ecological impacts on their importance and trying to quantify them. For an overall environmental analysis of a fisheries production system this methodology is slightly limited. A focus on environmental stressors and energy use should be incorporated in valuing the sustainability of fish products.

6.3 Comparison with other studies

The dataset from EAP has being used for this research, shows an energy requirement of 194 MJ per kg of fresh fish. This number is a very general statement, but it shows that the outcome of the research for the range of the energy requirements for both systems is correct. The North Sea Foundation (www.noordzee.nl/visserij, 2007) gives a general statement that 1 kg of caught sole corresponds with 4 liter of fuel use, which is about 140 MJ. Shrimp farming gives an outcome of 129-205 MJ per kg (Larsson et al., 1994) and cage-cultured salmon gives an energy requirement of 97-107 MJ (Folke, 1988). These results from the literature show that the sole production system, whether it is fishing or farming, has a higher energy requirement than for other species.

The direct energy input from fossil fuels is for fisheries around 75-90% of the total energy requirement and the remaining 10-25% is allocated for maintenance, construction etc. (Tyedmers, 2001). The same result is found for the sole fisheries production system in this research. Tyedmers (Tyedmers, 2001) also shows that the total energy requirement depends heavily on the type of fishing gear being used. Trawling has an energy requirement of around 35 GJ/t and purse seining varies between 1.8 and 10 GJ/t (Tyedmers, 2001). For the purse seining involved for the fish-food which is being used by Solea BV is an energy requirement of 5.4 GJ/t chosen for the data analysis. This is a well estimated average, but the energy input also could have been different according to this range.

The outcome of the environmental stressors is difficult to compare with other data since it only relies on the data from the energy analysis and similar literature is hard to find. Emissions from Swedish cod trawling show for NO\textsubscript{X} a similar outcome, but for SO\textsubscript{2} and CO\textsubscript{2} emissions about a factor 10 higher than for Dutch sole fisheries (Ziegler et al., 2003).
Economic allocation can be very important in mixed fisheries, like the beam trawling for sole and other species, but only when the species have a high economic value and there is many bycatch involved in the process (Ziegler et al., 2003). Thus pursuing the analysis with the data from the economic allocation seems justified.

In this research the environmental effect of the fish-food is not taken into account. For assessing and improving the sustainability of aquaculture practices, it is important to include this in the analysis (Papatryphon et al., 2004).

The ecosystem support area based on the EF analysis does not take into account marine systems and processes. Another method is to estimate the marine ecosystem support area. Hereby the primary production required to sustain the amount of landings is estimated per species by using its trophic level (Tacon, 2005). Although this is a way to incorporate the marine ecosystem, it is still not an applicable and reliable methodology.

The general assumption is made that aquaculture is better for the (marine) environment than fisheries and that it can fill the need for fish food supply. But this statement is mostly true for herbivorous fish and not for all species (Naylor et al., 1998). Fish species that are positioned lower in the food system, mostly herbivorous, are more sustainable than higher trophic leveled fish (Wolowicz, 2005). Naylor et al. (Naylor et al., 1998) also states that aquaculture of carnivorous species, like salmon and shrimp, but also sole, is rather depleting the supply of fish than adding to it. The reason is that aquaculture production relies on fish to feed their fish.

6.4 Conclusions

This research shows that fisheries has a high energy requirement due to the use of fossil fuels for navigating and catching. Due to this high fossil fuel use, the system also requires a high ecosystem support area. It also has a high ecological impact due to the bycatch and ecological damage by trawling the sea floor.

The basic sole aquaculture production system as such has a small ecological impact because it does not rely on antibiotics or young fish from the wild, which are important ecological impacts for aquaculture production systems. The use of fish-food gives the most ecological impact in the ‘traffic light’ method. The electricity for pumping the water around in the raceways corresponds to a high direct energy requirement. Also the fish-food production and catching the fish for the fish-food is a large share of the energy requirements. For fish-food the energy requirement is very low compared to the beam trawling for sole, this because it is twenty times more efficient.

Even though the sole aquaculture production system does not rely on sole from the wild, the environmental impact of this production system should be kept in mind. For the common sole the aquaculture production is developing fast and this could give rise to a larger environmental impact. As this research shows the overall environmental impact of sole aquaculture is lower than that of the current wild fisheries.
7  RECOMMENDATIONS

7.1  Improvements for sole & best possible scenario

The fisheries production system can be improved on two aspects. One is the beam trawling method, which is causing high ecological impact and high energy use. Methods such as passive fishing (like that is being used in Denmark) can be used to catch flatfish like sole. Another way to reduce the energy is by using electrical pulses instead of the heavy chains that are connected to the beam. Not only will the energy reduce, because the weight is smaller, also it is likely to assume that the bycatch will be somewhat lower and the damage to sea bottom is reduced. Another way to improve the fisheries is by policy measures, which can be directed at quota, fishing activity or mesh size. The most efficient way is to reduce the fishing intensity, whereby the stock will improve significantly. Consequently less fuel is needed to catch the same amount of sole. Also the ecological impact will reduce, because less time will be spent on fishing, so the beam trawling effort is reduced.

For the aquaculture production system of Solea BV it is most important to increase the current production volume. In that way it can compete with the existing market of sole fisheries. To improve the sustainability of the production system a new method for circulating the water is essential. Now it is pumped through each raceway separately. When the water is pumped through the highest raceway and then flows down through each raceway, the energy for water circulation can be reduced by a factor 2 to 4. But then an adaptation for the filtering the water between the raceways should be made. Also, according to Andries Kamstra from Solea BV, the natural gas use can be reduced significantly as well. It has been decreasing already for the last years. For Solea BV it is also important that more female fish are present in the system, which can be achieved by specific regulation of the temperature during the breeding. Females grow faster and become larger than the males, which makes them more profitable. And because they are in the system for a shorter period of time, the use of energy and materials reduces as well. To reduce the ecological impact other source of food can be used which contains less fish meal and fish oils. The pressure on the wild stocks, which are used for this fish-food can hereby be reduced. Finally Solea BV can rely solely on sustainable energy sources, e.g. by installing a wind mill, which reduces the overall environmental impact significantly.

It is possible that some of these improvements are established for both systems within five years. For the best possible scenario we assume that the fisheries will improve through policy measures. One should hereby focus on reducing the fishing intensity, which leads to an increase in the stock biomass. For fisheries the amount of fuel is assumed to be reduced by half due this policy related improvement. For Solea BV it is most likely that within five years the water can be circulated more efficiently and that other fish-food is being used. If that happens, a shift towards a more sustainable sole production system will take place. For fisheries this is a major reduction in the fuel use, for aquaculture this is a major reduction in the electricity use and reducing the ecological impact. So energy requirements for both systems can become almost equal, and the ecological impact for both will reduced, but more so for the aquaculture than for the fisheries. This is due to the beam trawling method for fisheries. Consequently the aquaculture at Solea BV still will be more sustainable, based on the lower ecological impact. And Solea BV has the advantage that it can always deliver to the market, instead of the fisheries where the landings fluctuate with the seasons.
7.2 Proposal new methodology

This research makes use of several different methodologies, and all of them have their pros and cons. With the knowledge of this research it can be useful to propose a new methodology for assessing fish products on their sustainability. The goal of this methodology is not to certify the fish products, but to value their sustainability so the consumer can make an informed decision.

The new sustainability methodology should incorporate both ecological and environmental aspects. For valuing the sustainability of fish products both aspects are important. Hereby the questionnaire of the North Sea Foundation is kept in mind, but expanded with environmental aspects, such as direct and indirect energy requirements. Performing a thorough LCA is not necessary, but key environmental stressors should be assessed. And estimating an ecological support area by using an EF does not contribute substantially in this new methodology.

A maximum of ten categories per production system should be chosen, which meet the Pareto principle, implying that only the factors that contribute the most are taken into account. It is important to keep the maximum at ten, because then it is uncomplicated and easy to compare both production systems. Categories such as energy, feed-conversion (aquaculture), discharge (aquaculture), bycatch (fisheries) should be taken into account. These ten categories should be valued according to their weighted importance. The importance of each category should be agreed upon by various experts from different fields. At present SMK (Stichting Milieukeur), the North Sea Foundation, MSC (Marine Stewardship Council) etc. all use their own non-standardized criteria and principles.

Because this methodology is a static method, the valuation of the sustainability of the fish species and their production system should be reviewed periodically.

7.3 Further research

For this research the common sole was used as a model species to estimate the overall environmental impact by using the different methodologies. It is useful to apply this research to other species for comparison.

Also it is best to expand the boundaries that were set for this research. A more extensive analysis is necessary to ensure that certain processes are not invalidly left out of the analysis. Finally an economic analysis can also be of importance for comparing the two production systems. Especially when keeping in mind the increasing fossil fuel price, which will influence the fisheries system the most because they rely more on fossil fuels. Therefore the market price will increase which has consequences for the consumer behavior.

To compare a fisheries or aquaculture production not only to each other but also with meat products it is important to incorporate a protein efficiency analysis. Hereby the amount of food used is converted per amount of protein instead of per mass. Depending on the diet of the species the feed conversion can be higher or lower. This can depend on the diet and lifestyle; cool or warm-blooded versus herbivore or carnivore species.
ACKNOWLEDGEMENTS

First of all I would like to thank my two supervisors Ton Schoot Uiterkamp from IVEM, Groningen and Adriaan Rijnsdorp from IMARES, IJmuiden for their contribution, valuable comments and support to the project. I would also like to thank Andries Kamstra who provided me with information about his company Solea BV. Many thanks to the IVEM staff, especially two members, René Benders and Henk Moll, for their input during the process. Also thanks to the North Sea Foundation, especially Esther Luiten, for sharing their knowledge.

Finally I would like to thank Frank Akkerboom, who motivated me throughout the whole process and helped me finishing this report.
REFERENCES


FAO. (2004). The state of the world fisheries and aquaculture: SOFIA.


APPENDICES

A1 North Sea Foundation methodology

Questionnaire for wild captured fish species

The following questions need to be answered to categorize the fish species in green, yellow or red:

A. Biological aspects of the fish species
   - Is the species on a national or international list of endangered species?
   - Is the stock within safe biological limits, according to the International Council for Exploration of the Sea (ICES)? If there is no ICES data available, are there data available on the stock status?
   - Is the species sensitive for fishing pressure? (based on speed of growth, age of maturity and maximum age)
   - Does the species have specific life features what makes it sensitive to fishing pressure? Examples: migration, spawning in aggregations, geographical

B. Ecological effects of the fishing practices
   - Is a part of the total landings bycatch? (e.g.; other species or undersized fish)
   - Are there discards and how many? (both non-target species like dolphins and target species like undersized fish)
   - Bonus: If the species is bycatch, is this of low economical value by discarding it a lot?
   - Is the fishing method causing damage to the sea bottom and the ecosystem?
   - Is the fishing method causing substantial ecosystem changes like cascade effects or food chain effects? (indirect effects)

C. Policies
   - Is there a policy system for the fishing practices used for catching the fish species? (varying from completely controlled to minimum policy measures)
   - Are the policies specifically focused on the key problems in the fisheries? (like stock status, bycatch, ecosystem damage, illegal fisheries)
   - Are the implementation and control of the system effective to guaranty the productivity of the fish and the integrity of the ecosystem on the long term?
   - Are the fisheries or the policies aiming at full traceability of independent (third party) certification?
   - Does the policy system substantially contribute to the local communities (social or economical: human rights, economic stability, food)?
**Questionnaire for aquaculture species**
The following questions need to be answered to categorize the fish species in green, yellow or red:

A. Production system and fish-food
- Does the production system use lots of energy? (low, medium or high energy use)
- Does the production system use or contaminate fresh water sources which make it useless for other purposes?
- Are there by the construction of the system changes made to the environment (on- or off-shore)? (Is there loss of natural habitat?)
- Does the production system influence the health of the species?
- Does the system rely on feeding?
- How much wild fish is needed per kg of produced fish?
- Does the fish-food contains by- or rest products or is there fish being specially produced or fished for this purpose?
- Is the fish-food produced sustainably?
- Are there additives used in the fish-food which influence the normal behaviour and/or the health of the species? (hormones, growth regulating additives, etc.)

B. Ecological effects of the production system on the environment
- Are there contaminants discharged in the environment? (chemicals, medicines, faeces, etc.)
- If the system relies on young fish from the wild: is the species overfished, threatened, or protected?
- Is there any potential contamination risk for wild species around the production site? (transfer of diseases or parasites)
- Is there a risk of escapes and if so, does it have possible negative ecological effects?

C. Policies and management
- Are the production systems strategically located taking the environment into account? (Is there a kind of spatial planning or integrated coastal zone management?)
- Does the production system comply with environmental regulations?
- Are there regulations to prevent the escapes or introducing exotic species?
- Are there regulations to prevent the transfer of diseases?
- Is the product or the farm certified by an independent party?
- Does this type of aquaculture in general contribute to local communities either socially or economically?
## A2 Data fisheries

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### Economic allocation

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Data sources:
- Fuel use LEI
- Landings LEI
- Maintenance EAP
# A3 Data aquaculture

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A4 Data environmental impact

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<th>N2</th>
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</tr>
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<td>transport fish-food (Norway) (tonkm)</td>
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<td>0.01</td>
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<tr>
<td>total (Peru)</td>
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<td>16.73</td>
<td>12.26</td>
<td>0.10</td>
<td>0.07</td>
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<td>17.80</td>
<td>30.07</td>
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