Using Blue Mussels as a Tool for Mitigating Eutrophication in the Baltic Sea

Linnea Henriksson
Johanna Stähle

Supervisor: Carina Sundberg
Examiner: Niclas Svensson
Abstract

Eutrophication is a consequence of excess nutrients in the water which leads to increased algae growth, reduced water transparency and hypoxic bottoms. This is the biggest environmental problem for the Baltic Sea which recently has resulted in stricter legislations and other initiatives to help the Baltic Sea to recover. However, the actions to reduce the nutrient input to the Baltic Sea have so far mainly been land-based. These actions seem to not be enough since the eutrophication continues to be a problem for the Baltic Sea. Farming blue mussels has shown to have a mitigating effect on the eutrophication and could thus be a complementary action. Blue mussels are filter-feeding species which means that they filter water for food and thus eat phytoplankton and accumulate nutrients at the same time. When the blue mussels are removed from the sea, so is the nutrients accumulated in the mussels, resulting in a mitigation of nutrients and thereby the eutrophication. Due to the brackish water with the low salinity in the Baltic Sea, the blue mussels farmed there do not grow bigger than around 3 cm. This means that the mussels are not suitable for human food production and the harvested mussels need to be used for something else, even though the farming itself is an environmental action. Three possible mussel products from valorisation of the Baltic Sea blue mussels have been identified; producing mussel meal, biogas or compost.

Region Östergötland is involved in a project, Baltic Blue Growth, with the main objective to study how to use mussel farming as an environmental measure and which of the three valorisation options is the most beneficial from an environmental perspective. This study is a part of their investigation to reach their goal and will study their mussel farm in St. Anna and the three valorisation options from an environmental perspective. The aim of this study is thus to investigate the net nutrient reduction from a mussel farm in the Baltic Sea in combination with the contribution to climate change. This is done from a life cycle perspective to include the valorisation of the mussels into the different products mussel meal, biogas or compost. For this, an existing farm in the archipelago of St. Anna, Östergötland, Sweden is studied. The main results show that there is a nutrient reduction from the mussel farm and this is not majorly affected regardless of which valorisation option that is chosen. However, the mussel farm does have an impact on climate change and the magnitude of the impact varies for the three valorisation options. The results of the sensitivity analysis show that the result from the life cycle can be improved with future improvements of the mussel farm and transportation. The nutrient reduction can become larger and the impact on the climate change can be reduced. Outside the result from the life cycle analysis it is discussed that there are other future improvement possibilities in the production of the mussel products, which would impact the result. The mussel farm and the mussel products also have other positive impacts that is not included in the life cycle analysis but discussed in the study, such as increased water transparency, recycling of nutrients and reduction of over fishing. However, the mussel farm could also have negative impacts, such as emissions of microplastics and locally increased sedimentation which affect the hypoxia. Those are discussed in this study but the probability and possible impact of them are not fully investigated and need further research.

Keywords: Life cycle analysis (LCA), recycling of nutrients, blue mussels, mussel farm, mussel meal, biogas, compost
Acknowledgement
This Master Thesis, written in the spring semester 2018, is the result of five years studying of Energy-environment-management M. Sc. in engineering at Linköping University. The authors are Linnea Henriksson and Johanna Ståhle and we would like to thank our examiner, Niclas Svensson, and supervisor, Carina Sundberg, for valuable help and guidance in our work. We also want to say thank you to our opponents Lena Ländin and Cassandra Wu for the criticism that helped us improve our thesis. Lena Tasse, our mentor at Region Östergötland, a big thank you to you for the possibility to do our work together with you and Region Östergötland and for introducing us to the blue mussel community where we could find valuable information and contacts. Also, a thanks to the people who took the time and energy to answered us at times very specific questions for the data collection; Erik Nordell at Tekniska Verken AB, Ola Palm at Research Institutes of Sweden, Sverre Aarønen at Nofima and the mussel farmer Mats Emilsson. Finally, lots of love to all our classmates and everyone else we have gotten to know at Linköping University for making these five years of studying the best ones, even during the hard times!
Table of content
1 Introduction ................................................................................................................. 8
  1.1 Description of the problem .................................................................................. 8
  1.2 Objective .............................................................................................................. 9
  1.3 Research questions ............................................................................................ 9
2 Closing the loop ......................................................................................................... 10
3 Eutrophication in the Baltic Sea ............................................................................... 11
4 Blue mussel ............................................................................................................. 14
  4.1 Mussel meal .......................................................................................................... 15
  4.2 Biogas .................................................................................................................. 15
  4.3 Mussel compost .................................................................................................... 16
5 Life cycle assessment ............................................................................................... 17
  5.1 Goal and Scope definition .................................................................................. 17
  5.2 Inventory analysis ............................................................................................... 17
  5.3 Impact assessment ............................................................................................... 18
    5.3.1 Characterization factor ................................................................................ 19
  5.4 Limitations ........................................................................................................... 19
6 Previous research .................................................................................................... 21
7 Method ...................................................................................................................... 23
  7.1 Scenarios ............................................................................................................. 24
  7.2 Data collection ...................................................................................................... 25
  7.3 Modelling ............................................................................................................. 26
    7.3.1 Impact Assessment ....................................................................................... 26
  7.4 Analysis and discussion ....................................................................................... 29
8 Detailed description of the scenarios ...................................................................... 30
  8.1 Scenario 1 – Mussel farm ................................................................................... 30
    8.1.1 Source of errors ............................................................................................ 32
  8.2 Scenario 2 – Mussel meal ................................................................................... 34
    8.2.1 Source of errors ............................................................................................ 36
  8.3 Scenario 3 – Biogas ............................................................................................. 36
    8.3.1 Source of errors ............................................................................................ 38
  8.4 Scenario 4 – Compost ......................................................................................... 39
    8.4.1 Source of errors ............................................................................................ 41
  8.5 Sensitivity analysis ............................................................................................... 41
    8.5.1 Future development Scenario 1 – Mussel farm ........................................... 41
    8.5.2 Transport variation ......................................................................................... 42
List of figures

Figure 1. A simplification on how an excess of nitrogen and phosphorus from human activity affects the marine environment in respect of eutrophication ......................................................... 11
Figure 2. Picture of mussels from the farm in St. Anna, Östergötland. Reference picture .................. 14
Figure 3. Illustration of the methodology used in this study, which is based on the general LCA methodology ........................................................................................................... 23
Figure 4. Illustration of the studied system and the overall constellation of the scenarios. ............ 25
Figure 5. Illustration of the 8 stages the life cycle is divided into when presenting the result ....... 29
Figure 6. Illustration of Scenario 1 – Mussel farm ........................................................................ 30
Figure 7. Illustration of the long line technique for mussel farming ............................................. 31
Figure 8. Illustration of Scenario 2 – Mussel meal ........................................................................ 34
Figure 9. Illustration of Scenario 3 – Biogas ................................................................................. 36
Figure 10. Illustration of Scenario 4 – Compost .......................................................................... 39
Figure 11. The result for Scenario 1 – Mussel farm within the eutrophication impact category based on 1 tonne mussels ......................................................................................... 47
Figure 12. The result for Scenario 1 – Mussel farm within the climate change impact category based on 1 tonne mussels .......................................................................................... 48
Figure 13. The result for Scenario 1 – Mussel farm within the eutrophication impact category based on 75.5 tonne mussels .......................................................................................... 49
Figure 14. The result for Scenario 1 – Mussel farm within the climate change impact category based on 75.5 tonne mussels .......................................................................................... 49
Figure 15. The result from the sensitivity analysis Future development Scenario 1 – Mussel farm within the eutrophication impact category based on 1 tonne mussels ........................................... 51
Figure 16. The result from the sensitivity analysis Future development Scenario 1 – Mussel farm within the climate change impact category based on 1 tonne mussels ........................................... 52
Figure 17. Comparison of the reduction of eutrophication for Scenario 2 – Mussel meal, Scenario 3 – Biogas and Scenario 4 – Compost in relation to each other ...................................................... 53
Figure 18. Comparison of the contribution to climate change for Scenario 2 – Mussel meal, Scenario 3 – Biogas and Scenario 4 – Compost in relation to each other ...................................................... 53
Figure 19. The result for Scenario 2 – Mussel meal, Scenario 3 – Biogas and Scenario 4 – Compost within the eutrophication impact category based on 1 tonne mussels ........................................... 54
Figure 20. The result for Scenario 2 – Mussel meal, Scenario 3 – Biogas and Scenario 4 – Compost within the climate change impact category based on 1 tonne mussels ........................................... 56
Figure 21. The result for Scenario 2 – Mussel meal, Scenario 3 – Biogas and Scenario 4 – Compost within the eutrophication impact category based on 75,5 tonne mussels ......................................... 57
Figure 22. The result for Scenario 2 – Mussel meal, Scenario 3 – Biogas and Scenario 4 – Compost within the climate change impact category based on 75,5 tonne mussels ......................................... 58
Figure 23. The result from the sensitivity analysis on transportation variation within the eutrophication impact category based on 1 tonne mussels ............................................................... 60
Figure 24. The result from the sensitivity analysis on transportation variation within the climate change impact category based on 1 tonne mussels ............................................................... 61
Figure 25. The normalized result within the eutrophication impact category based on 75.5 tonne mussels .......................................................................................................................... 62
Figure 26. The normalized result within the climate change impact category based on 75.5 tonne mussels .......................................................................................................................... 63
List of tables

Table 1. Presentation of the persons who have been contacted during the data collection ............ 26
Table 2. Presentation of the substances that are recalculated to N-equivalents and inserted into ILCD’s marine eutrophication method .................................................................................................................. 28
Table 3. Presentation of the inputs and outputs used in Scenario 1 – Mussel farm ......................... 32
Table 4. Presentation of the inputs and outputs used in Scenario 2 – Mussel meal .......................... 35
Table 5. Table of the nutrient numbers used when calculating to nutrient content in the biofertilizer after the biogas production ................................................................. 37
Table 6. Presentation of the inputs and outputs used in Scenario 3 – Biogas ............................... 38
Table 7. Table of the nutrient numbers used when calculating to nutrient content in compost after the compost production ................................................................. 40
Table 8. Presentation of the inputs and outputs used in Scenario 4 – Compost .............................. 40
Table 9. Inputs and outputs for the three cases in sensitivity analysis of Scenario 1 – Mussel farm with numbers presented for both 1 harvest and 1 tonne of mussels ................................. 42
Table 10. Presentation of the inputs used in the sensitivity analysis for production sites for mussel meal production ........................................................................................................ 44
Table 11. Presentation of the inputs used in the sensitivity analysis for production sites for biogas production ........................................................................................................ 45
Table 12. Presentation of the inputs used in the sensitivity analysis for production sites for compost production ........................................................................................................ 46
Table 13. A recap of the different transport variations of Scenario 2 – Mussel meal, Scenario 3 – Biogas and Scenario 4 – Compost ................................................................. 59
1 Introduction

This first chapter introduces the background for why this study is important and initiated. It includes a description of the problem and presentation of the objective and the research questions.

1.1 Description of the problem

For coastal waters, eutrophication has been considered one of the biggest threats to marine ecosystem (Andersen et al., 2006). Eutrophication means an excess of organic matter, mostly the nutrients nitrogen (N) and phosphorus (P), which contributes to increased algae growth (Andersen et al., 2006; Warell, Eklund and Fonselius, 2018). The intensive algae growth leads to poorer water quality and hypoxic or even anoxic bottoms (Ek Henning and Åslund, 2012; WWF, 2018). The nutrients exist naturally in aquatic environments, but due to human activities the concentrations have increased and created eutrophication and in order to break the trend the nutrient input must be reduced. Since the early 1900s the Baltic Sea has gone from an oligotrophic to a eutrophic sea due to anthropogenic nutrient inputs (Larsson, Elmgren and Wulff, 1985). Today, the biggest environmental threat to the Baltic Sea is the eutrophication and around 80 % of the nutrient input comes from land-based, anthropogenic activities such as run-off from agriculture and wastewater (WWF, 2018). The problem with eutrophication in the Baltic Sea, has stimulated a desire to form mobilized actions via both EU directives, e.g. the water framework directive 2000/60/EC, and initiatives such as HELCOM (Baltic Marine Environment Protection Commission – Helsinki Commission). HELCOM was formed in 2007 and includes an agreement between the nine countries around the Baltic Sea to take action against the poor ecological status of the Baltic Sea, referred to as the Baltic Sea Action Plan (BSAP) (HELCOM, 2007). BSAP contains how much each country must reduce their outputs of nitrogen and phosphorus to reach the target of a “good environmental status” in respect to eutrophication (HELCOM, 2007). All of the planned and implemented actions in Sweden are land-based, focusing on the reduction of nutrients reaching the Baltic Sea (Petersen et al., 2014). Examples of this are more environmental friendly agriculture, better wastewater treatment and construction of wetlands. However, these actions do not reduce the nutrient input sufficiently to reach the goals. Furthermore, bound nutrients in the sediment are also released as a result of hypoxic bottoms, contributing further to eutrophication. A report from WWF (2018), shows that not one country will succeed within the deadline. Furthermore, according to Naturvårdsverket, Sweden’s environmental quality standard Zero eutrophication (an implementation of the water framework directive 2000/60/EC), will not be reached in time with the actions implemented and planned today (Ek, 2018).

A possible complementary nutrient reduction method identified by many researchers is farming blue mussels (Lindahl, 2004; Ek Henning and Åslund, 2012; Petersen et al., 2014; Tasse, 2017). Blue mussels filter the water for phytoplankton and particles, accumulating nutrients in the process and increasing the water transparency (Ek Henning and Åslund, 2012; Tasse, 2017). When harvested, the nutrients are taken from the sea to land and the eutrophication is reduced. Blue mussels naturally inhabit the Baltic Sea, however, due to the low salinity they grow more slowly and do not become as big as in salt water (Stadmark and Conley, 2011; Nilsson and Öhrling, 2013; Tasse, 2017). Several projects, both national and international, have the ambition to study mussel farming in the Baltic Sea to investigate the potential of big-scale farms as nutrient reduction measures, one example is the EU project Baltic Blue Growth (BBG) where Region Östergötland is the lead partner (Tasse, 2017). The aim of BBG is to study mussel farming from a nutrient reduction perspective by investigating how to take mussel farming in the Baltic Sea from small scale to big scale (Tasse, 2017). One of the mussel farms in the BBG project is studied in this LCA and is located in the archipelago of St. Anna. The farm in St. Anna is still in small scale and there are some areas that need to be addressed before they can decide whether
to expand the farm. One of those areas is whether there is a net reduction of nutrients from the mussel farm when also the energy and material for maintenance and harvest are included. In other words, does mussel farming actually work as a measure for mitigating eutrophication? Another area is to decide how to handle the harvested mussels. There is more than one aspect to consider in this decision, and one of them is the environmental aspect. Since the main purpose of the mussel farm is to help mitigate eutrophication, it is of interest to know how the different possibilities of handling the harvested mussels affect the net nutrient reduction of the mussels. Today, the blue mussels from the Baltic Sea are not approved by “Livsmedelsverket” for human consumptions (Tasse pers. com., 2018) and therefore, this is not considered as an alternative. Studies have identified other possible areas of use for the mussels where the main possibilities are mussel meal, biogas and compost (Kollberg and Lindahl, 2004; Olrog et al., 2008; Jönsson and Elwinger, 2009; Nordell, 2010; Nilsson and Öhrling, 2013). This is the origin of the study and to be able to determine the actual environmental performance the mussel farm needs to be investigated during its whole life cycle including the valorisation of the harvested mussels into the different mussel products, Mussel meal, Biogas and Compost. Previous research has been carried out on the nutrient reduction and environmental benefit from mussel farms, though not from a life cycle perspective when including the managing of the farm (Lindahl, 2004, 2011; Stadmark and Conley, 2011; Petersen et al., 2014). Irribarren (2010) did a life cycle assessment on mussel farms in Spain which also included the material and energy needed for the maintenance and harvest. Studies on suitability of mussels as feed, biogas and compost have also been made (Kollberg and Lindahl, 2004; Olrog et al., 2008; Jönsson and Elwinger, 2009; Nordell, 2010; Nilsson and Öhrling, 2013). Spångberg, Jönsson and Tidåker (2013) did a life cycle assessment on mussel farms in combination with using them as compost. However, to the authors’ best knowledge, no studies have been made on the life cycle of Baltic Sea mussels when the mussels are used for mussel meal production or biogas production. Furthermore, the possible environmental cost in form of contribution to climate change of mussel farming as a eutrophication mitigation measure has not been studied before. The identified gap in the literature is thus that no study have done a life cycle analysis (LCA) on mussel farms when both studying the possible reduction in eutrophication and contribution to climate change and also including a comparison of different valorisation options. The authors aim with this study is to contribute to filling this gap, by doing an LCA on the mussel farm and including the transportation and different valorisation options mussel meal, biogas and compost. The LCA is performed on the existing blue mussel farm in St. Anna, Östergötland, which is one of the farms in the BBG project. The expectation from Region Östergötland is that this study can be used in the decision making whether the county of Östergötland can use mussel farming as a measure for mitigating eutrophication as well as the management option for the harvested mussels from these farms. This study was initiated by Lena Tasse at Region Östergötland on the premises presented above and then further developed by the authors together with the examiner and Lena Tasse.

1.2 Objective

The main objective of this study is to evaluate the net nutrient reduction in the Baltic Sea of farmed blue mussels including the production of the different mussel products mussel meal, biogas, and compost, in comparison to the systems’ contribution to climate change.

1.3 Research questions

1. What is the net reduction of nitrogen and phosphorus and the contribution to climate change of farmed blue mussels in the Baltic Sea?

2. What is the net reduction of nitrogen and phosphorus and the contribution to climate change of the different mussel products biogas, mussel meal and compost compared to each other?
2 Closing the loop

The industrial ecology concept aims at making an industrial system compatible with the natural ecosystems by understanding how it functions and interact with the environment (Erkman, 1997). For this understanding, material and energy flows need to be determined and mapped (Erkman, 1997). The global economy is dominated by a linear model where products are produced from raw material, used and then disposed (Saavedra et al., 2018). To move from this linear model and decrease the environmental impact a circular model has arisen (Moreau et al., 2017). This model is called circular economy and was introduced by the British economists Pearce and Turner in 1989 (Cuadros Blázquez et al., 2018). The aim of circular economy is to keep products, components and materials in a cycle and has gained attention in society in recent time (Ellen MacArthur Foundation, 2015; Sauvé, Bernard and Sloan, 2016). In a circular economy, resources would be captured and valorised (Ellen MacArthur Foundation, 2017), both to close the material cycles and to increase resource efficiency which is what circular economy revolve around (Moreau et al., 2017). Many natural flows, such as nutrient cycles, are disturbed by human activity which can create an excess or shortage of important substances and thus cause damage to ecosystems (Ellen MacArthur Foundation, 2017).
3 Eutrophication in the Baltic Sea

Eutrophication means an excess of nutrients, phosphorus (P) and nitrogen (N), which increases the production of phytoplankton, zooplankton and algae (Havsmiljöinstitutet, Havs- och vattenmyndighetene and Naturvårdsverket, 2016). Fresh water environments most often has a P-shortage compared to other nutrients and is therefore seen as P-limited, implying that an addition of phosphorus will increase biomass growth whereas an addition of nitrogen will not (European Comission, 2011; Henryson, Hansson and Sundberg, 2018). In marine environments the relation in general is the opposite, making them N-limited (European Comission, 2011; Henryson, Hansson and Sundberg, 2018). The Baltic Sea however, is said to be both N- and P-limited, implying that both nutrients contribute to eutrophication and should be considered when studying eutrophication in the Baltic Sea (Henryson, Hansson and Sundberg, 2018). An increased production decreases the water transparency and thus the depth for sunlight to reach (HELCOM, 2009). This means that the production of algae in the deep water reduces since algae need sunlight for the photosynthesis. With an excess of nutrients and low water transparency, the short-lived microalgae thrive and thus the sedimentation increases. With the increased need for degradation, the oxygen demand is also increased which leads to a hypoxic and sometimes even anoxic seabed (Havsmiljöinstitutet, Havs- och vattenmyndighetene and Naturvårdsverket, 2016). Since less algae can survive in the deep water, not enough oxygen is produced to prevent formation of hypoxic bottoms. Additionally, nutrients in the sediment, called the internal load, are released during hypoxic conditions and thus contributing further to eutrophication (Conley and Zillén, 2008). The enhanced load of nutrients is a result from anthropogenic activities such as agriculture, combustion of fossil fuels and not 100 % purified waste water. Figure 1 shows the cause-effect chain of enhanced nutrient input graphically.

![Figure 1](image-url)
Phosphorus and nitrogen, as carbon, oxygen and hydrogen, are essential for humans, animals and plants (Pedersen et al., 2018), but when there is an excess of those nutrients the ecosystem is disturbed as explained above. Both phosphorus and nitrogen have natural cycles and those cycles can be disturbed, either by a shortage or an excess of nutrients, where an excess lead to eutrophication. The phosphorus cycle goes between soil and water and the cycle period can be days, weeks or years (Pedersen et al., 2018). The nutrient is, similar to carbon, classified as a fossil mineral and the cycle is disturbed since the phosphorus rock is mined for anthropogenically use of phosphorus (Rockström et al., 2009). The main anthropogenic use of phosphorus is within mineral fertilizer and the agriculture, and the nutrient is today classified as a scarce resource since the remains of phosphorus rock is decreasing (Cordell, Drangert and White, 2009; Spångberg, Jönsson and Tidåker, 2013; Petersen et al., 2014). Because of this, and in line with the circular economy concept, it is of interest to find new and recyclable sources of phosphorus. The nitrogen cycle is a bit more complex than the phosphorus cycle and goes between soil, water and air (Bolin and Elding, 2018). As commonly known, the main part of the air we breathe consists of nitrogen, however, this form of nitrogen is not available for plants and animals to use (Galloway et al., 2004). The transformation from nitrogen gas to so-called plant available nitrogen (mostly ammonia, nitrate and nitrite) is a part of the natural cycle and is done by nitrogen fixating bacteria or algae (cyanobacteria) (Bolin and Elding, 2018). This natural cycle of nitrogen is mainly disturbed by artificial nitrogen fixation, for production of mineral fertilizer, and combustion of fossil fuels which releases nitrogen oxides (Mosier, Syers and Freney, 2013; Bolin and Elding, 2018).

Rockström et al. (2009) developed a way of measuring if the impact from human activities stayed within the limits of the Earth, in line with the Industrial Ecology concept, and called those “The planetary boundaries”. There are nine planetary boundaries in total and one of them is “interference with the nitrogen and phosphorus cycles” (Rockström et al., 2009). The anthropogenic interference with the nitrogen cycle is measured as the amount of nitrogen gas removed from the atmosphere for human use and the phosphorus cycle as the quantity of phosphorus (P) flowing into the oceans (Rockström et al., 2009). In 2009 the limit of the nitrogen cycle was crossed (Rockström et al., 2009) and in 2015 both the limit for nitrogen and phosphorus were crossed (Steffen et al., 2015). This means that we transformed too much nitrogen gas to plant-available nitrogen and mined too much phosphorus from the phosphorus rock in respect to what Rockström (2009) identified is within the planets boundaries to handle without negative consequences.

Eutrophication is a serious threat to many coastal areas (Spångberg, Jönsson and Tidåker, 2013) and for the Baltic Sea it is the biggest threat to the marine environment and its inhabitants (HELCOM, 2009; Naturvårdsverket, 2009). The Baltic Sea was in the early 1900s an oligotrophic sea but due to enhanced nutrient input the Baltic Sea is now highly eutrophicated (Larsson, Elmgren and Wulff, 1985; HELCOM, 2009; Havsmiljönstitutet, Havs- och vattenmyndigheten and Naturvårdsverket, 2016). As mentioned, the sources for excess nutrients are many and to tackle this problem the countries around the Baltic Sea need to cooperate. Therefore, those countries has joined together in a commitment to mitigate the eutrophication in the Baltic Sea, called HELCOM (HELCOM, 2009; Naturvårdsverket, 2009). EU directive, e.g. the water framework directive 2000/60/EC regarding eutrophication has resulted in national regulations for Sweden, for example the environmental quality objective “Zero eutrophication” (Havs- och vattenmyndigheten, 2015). Both in the action plan within HELCOM (Baltic Sea Action Plan - BSAP) and the national quality objective, the main objective is to reach “Good environmental status” (HELCOM, 2007; Havs- och vattenmyndigheten, 2012). In HELCOM, an action plan was created for the countries to follow four focus areas to reach good environmental status for the Baltic Sea to 2021 where eutrophication is mentioned as one of the areas (HELCOM, 2007). Within eutrophication five objectives were identified to describe when good status is reached which are;
“Concentrations of nutrients close to natural levels”, “Clear water”, “Natural levels of algal blooms”, “Natural distribution and occurrence of plants and animals” and “Natural oxygen levels” (HELCOM, 2007). To achieve this status Sweden has committed to do several measurements on land to reduce the nutrient input to the Baltic Sea (HELCOM, 2007; Naturvårdsverket, 2009). These measures aim at reducing the excess of nutrients that originates from anthropogenic sources which mainly consist of run-off from agriculture and wastewater from communities and industries (Naturvårdsverket, 2009; Ejhed et al., 2016). Measures to reduce the nutrient input include, among other things, construction of wetlands, better agriculture and improved purification of wastewater (HELCOM, 2007; Naturvårdsverket, 2009). Both wetlands and wastewater treatment plants help, as mentioned, to reduce eutrophication but they have an impact on other areas. Wetlands takes up land areal and the construction of wetlands has an impact on, for example, climate change (Garfi, Flores and Ferrer, 2017). Wastewater treatment plants use material resources and energy both for construction and the daily management which has an impact on, for instance climate change (Åmand et al., 2016). The evaluation today regarding the environmental quality objective “Zero eutrophication” and the nutrient reduction commitment within BSAP, indicates that Sweden will not reach either of these goals within the timeframe of 2020 (Sveriges miljömål, 2018; WWF, 2018).
4 Blue mussel

Blue mussels, Latin *Mytilus edulis* (Linne, 1758), are bivalve molluscs which contains of a meat fraction enclosed by a shell consisting of two hinged parts, see *Figure 2*. As a marine animal it prefers high salinity water but also naturally inhabit brackish water such as the Baltic Sea (Stadmark and Conley, 2011; Hellmark, 2013; Nilsson and Öhrling, 2013; Tasse, 2017). Traditionally, the blue mussel is a delicacy for humans and mussel farming have therefore become a big industry globally. Mussel farming for human consumption has been an industry since the 1970’s in the high salinity waters on the Swedish west coast (Ek Henning and Åslund, 2012). In their right environment, blue mussels can become up to 10 cm long (Ek Henning and Åslund, 2012), but the lower the salinity the smaller they become and in the Baltic Sea they only grow to a size around 3 cm, see *Figure 2* (Stadmark and Conley, 2011; Hellmark, 2013; Nilsson and Öhrling, 2013; Tasse, 2017). To be used as human food, the mussels need to be big and unbroken, and normally around 30-40 % from the farms on the west coast is so called “mussel waste” (Olrog and Christensson, 2008). The mussel waste can be used for feed production, biogas production or compost production (Kungliga skogs- och lantbruksakademin, 2005; Olrog and Christensson, 2008; Svenskt Vattenbruk, 2017).

![Figure 2. Picture of mussels from the farm in St. Anna, Östergötland. Reference picture: Lena Tasse, Region Östergötland](image)

Blue mussels are a filter-feeding species, meaning they filter the water for food, and a 3 cm big mussel normally process about 2-3 litres of water per hour (Ek Henning and Åslund, 2012). In the filtering process they accumulate nutrients (N and P) and increase the water transparency and can therefore be named the “natural wastewater treatment plant of the sea” (Ek Henning and Åslund, 2012; Petersen et al., 2014). When harvested, the nutrients in the mussels are removed from the sea, and thus the nutrient excess in the water is reduced. Increased water transparency allows for sunlight to reach deeper in the water, creating a better environment for macroalgae growth and thus a better composition of biomass (HELCOM, 2017). Around existing blue mussel farms, this environmental benefit have been noticed (Hellmark, 2013) and indicates the possibility to use blue mussel farm’s as an environmental measure in eutrophicated areas (Lindahl, 2004; Kungliga skogs- och lantbruksakademin, 2005; Ek Henning and Åslund, 2012). Even though the primary function of the mussel farm is as an environmental measure, the harvested mussels must be used in some way, and if they are too small for human consumption they could instead be used the same way as “mussel waste”.

---

4 Blue mussel

Blue mussels, Latin *Mytilus edulis* (Linne, 1758), are bivalve molluscs which contains of a meat fraction enclosed by a shell consisting of two hinged parts, see *Figure 2*. As a marine animal it prefers high salinity water but also naturally inhabit brackish water such as the Baltic Sea (Stadmark and Conley, 2011; Hellmark, 2013; Nilsson and Öhrling, 2013; Tasse, 2017). Traditionally, the blue mussel is a delicacy for humans and mussel farming have therefore become a big industry globally. Mussel farming for human consumption has been an industry since the 1970’s in the high salinity waters on the Swedish west coast (Ek Henning and Åslund, 2012). In their right environment, blue mussels can become up to 10 cm long (Ek Henning and Åslund, 2012), but the lower the salinity the smaller they become and in the Baltic Sea they only grow to a size around 3 cm, see *Figure 2* (Stadmark and Conley, 2011; Hellmark, 2013; Nilsson and Öhrling, 2013; Tasse, 2017). To be used as human food, the mussels need to be big and unbroken, and normally around 30-40 % from the farms on the west coast is so called “mussel waste” (Olrog and Christensson, 2008). The mussel waste can be used for feed production, biogas production or compost production (Kungliga skogs- och lantbruksakademin, 2005; Olrog and Christensson, 2008; Svenskt Vattenbruk, 2017).

![Figure 2. Picture of mussels from the farm in St. Anna, Östergötland. Reference picture: Lena Tasse, Region Östergötland](image)

Blue mussels are a filter-feeding species, meaning they filter the water for food, and a 3 cm big mussel normally process about 2-3 litres of water per hour (Ek Henning and Åslund, 2012). In the filtering process they accumulate nutrients (N and P) and increase the water transparency and can therefore be named the “natural wastewater treatment plant of the sea” (Ek Henning and Åslund, 2012; Petersen et al., 2014). When harvested, the nutrients in the mussels are removed from the sea, and thus the nutrient excess in the water is reduced. Increased water transparency allows for sunlight to reach deeper in the water, creating a better environment for macroalgae growth and thus a better composition of biomass (HELCOM, 2017). Around existing blue mussel farms, this environmental benefit have been noticed (Hellmark, 2013) and indicates the possibility to use blue mussel farm’s as an environmental measure in eutrophicated areas (Lindahl, 2004; Kungliga skogs- och lantbruksakademin, 2005; Ek Henning and Åslund, 2012). Even though the primary function of the mussel farm is as an environmental measure, the harvested mussels must be used in some way, and if they are too small for human consumption they could instead be used the same way as “mussel waste”.
Mussel farming is not farming as in traditional aqua culture since no input of larvae, food or similar is needed (Lindahl, 2012). The idea of a mussel farm is simply to provide a surface for the naturally existing mussel larvae to attach to from where it is easy to harvest them. Several mussel farming techniques exist and the performance of these depends on the location of the farm and the specific conditions (Ek Henning and Åslund, 2012; Lindahl, 2012). The farming equipment are preferably added in the spring (April-May) for the larvae to attach and then normally harvested after two growth seasons (Ek Henning and Åslund, 2012). The mussel’s growth period is at its peak during summer and early autumn months and is called one growth season (Ek Henning and Åslund, 2012). How much mussels, ergo how much nutrients, that can be harvested from a farm depends on how close the ropes are placed and how close the plastic bands on the ropes are placed (Ek Henning and Åslund, 2012).

4.1 Mussel meal

Studies show how mussel meal can replace fish meal in animal feed, primary for pigs, fish and poultry (Kollberg and Lindahl, 2004; Jönsson, 2009; Randau, 2012). Similar to fishmeal, mussels contain both amino and fatty acids and have a high protein content (Jönsson and Elwinger, 2009, Fréon et al., 2017). Mussel meal could therefore replace fish meal to a one to one relation (Jönsson, 2009). A replacement for fish meal is of interest since the worlds’ seas, including the Baltic Sea, are over exploited due to intensive fishing (Engvall, 2012; Havsmiljöinstitutet, Havs- och vattenmyndigheterna och Naturvårdsverket, 2016). At the same time, the demand of animal feed is increasing, partly because the aqua culture is expanding which is a result of less fish in our seas (Engvall, 2012). Furthermore, fish meal can only be considered an organic fodder if the fish that it is made from are caught sustainably (Kommissionens förordning 2008/889/EG). For fish to be caught sustainably the stocks of the fish cannot be compromised and their reproduction potential cannot be jeopardized (European Commission, 2018). In summary, fish meal is an unstable protein source in animal fodder and mussel meal contain all the important substances which make it a suitable replacement. Studies where mussel meal in diets for laying hens show good promise, where no significant change occurs (Kollberg and Lindahl, 2004; Jönsson, 2009). The most significant change from the change of diets are the egg yolk pigmentation, it becomes darker with higher quota mussel meal (Kollberg and Lindahl, 2004; Jönsson, 2009). However, the taste is not affected in experiments done with up to 9 % mussel meal in the diet (Kollberg and Lindahl, 2004). There have been “talks” and testing with mussel meal as a replacement for fish meal for over 15 years (Kollberg and Lindahl, 2004). The subject has been more and more discussed and today there are some production for mussel meal (Biotep, 2018; Musselfeed, 2018).

4.2 Biogas

Biogas production can be divided into pretreatment, anaerobic digestion and upgrading. In the pretreatment phase the organic waste is grinded and then mixed with liquid and becomes a slurry. In Linköping, this slurry is pressed through a cyclone, which is added to the pretreatment, to remove larger particles such as plastics (from the municipal plastic bag that contains food waste) but also unwanted substrate input, like eggshells. This step in the pretreatment is not common, the pretreatment can include different steps at different production sites. The slurry continues to the hygienization where the slurry is heated up to 70 degrees to “kill” possible pathogens. According to an EU regulation animal biproducts must go through a hygienization before the actual biogas production (Kommissionens förordning 2011/142/EU). These stages are included in the pretreatment phase, after which the slurry goes to the digester. In the digester the temperature can vary between 25 and 60 degrees where the temperature depends on the microorganisms used in the process (Andersson, 2011). The time for digesting depends on the temperature and can thereby vary, higher temperature means faster process. In the digester biogas is produced under anaerobic conditions and consists of around 65 % methane and 35 % carbon dioxide. For the biogas to be used as fuel in vehicles
it needs to be upgraded, which means cleaning the gas of carbon dioxide, until the methane content is around 97%. This upgrading can be done with different processes, but in Linköping they mostly use an amino scrubber and sometimes a water scrubber. What is left from the digester, the digestate, contains a lot of nutrients and can be used as fertilizer on farming land.

4.3 Mussel compost

A challenge for organic farmers is to find sustainable fertilizer that is approved for them to use on their farms, here can mussels be of help as they contains nutrients from the seawater when harvested (Spångberg, Jönsson and Tidåker, 2013). To use mussels as fertilizer directly they need to be composted according to Swedish regulations, it also removes the odor from the mussels (Europaparlamentets och rådets förordning 2009/1069/EG; Kommissionens förordning 2011/142/EU). This compost process must happen in a certified compost facility and some sort of hygienization of the substrate (Kommissionens förordning 2011/142/EU). To create a compost substrate with good nutrient content, mussels are mixed with another substrate e.g. straw or bark (Olrog and Christensson, 2008; Olrog et al., 2008; Spångberg, Jönsson and Tidåker, 2013). After the mixing with another substrate, the compost process proceeds during a few months with a stirring a few times during these months (Olrog et al., 2008; Spångberg, Jönsson and Tidåker, 2013). To minimize the emissions during the process the composting happens in a controlled facility where emissions to soil and water can’t occur, only emissions to the air (Spångberg, Jönsson and Tidåker, 2013). After the composting time, where the time can vary from a few months to a year or longer, the compost can be spread on farm lands (Olrog and Christensson, 2008). During the process there are nutrient losses, mostly nitrogen but some phosphorus and potassium as well, where the nitrogen losses consist of air emissions of different nitrogen compounds (Spångberg, Jönsson and Tidåker, 2013). The nutrients losses can vary between different composting processes and from time to time, but there are still a lot of nutrients that can be returned to farm lands which creates a circular flow with the nutrients.
5 Life cycle assessment

Life cycle assessment (LCA) is a methodology for quantifying the environmental impact of a product or service through its whole life cycle (Baumann and Tillman, 2004; European Commission, 2010). It is widely used for analysing the environmental impact from a product or a service and also as a scientific and central support behind environmental sustainable decision making and policies (Baumann and Tillman, 2004; European Commission, 2010; Goedkoop et al., 2016). An LCA can for example be used to compare the environmental performance of different products, either for marketing purpose or for decision making (Baumann and Tillman, 2004; European Commission, 2010). It can also be used to identify areas to improve either in an existing product or process or during the design phase (Baumann and Tillman, 2004; Hetherington et al., 2014). The methodology is divided into four major steps; Goal and Scope Definition, Inventory Analysis, Impact Assessment and Interpretation of Results.

5.1 Goal and Scope definition

During an LCA, a model of the reality is studied, and it is important to remember that this model is a simplification of the reality (Goedkoop et al., 2016). The challenge is to make these simplifications in such a way that the results are not affected in a major way (Goedkoop et al., 2016). This is normally done during the Goal and Scope Definition, by carefully defining the goal with the study and its intended audience as well as the studied system, its boundaries and intended function (European Commission, 2010). Normally, an LCA has a “cradle-to-grave” perspective which includes the whole life cycle from production of the inputs, to transport, usage of the product and lastly waste handling (Baumann and Tillman, 2004). However, sometimes the life cycle is cut shorter, for example ending at the “gate” and thus not including the waste handling (Baumann and Tillman, 2004). From the definitions set in this stage, the methodological decisions such as data quality, presentation of the results and how to deal with allocations and assumptions are made (European Commission, 2010). Since it is in the Goal and Scope Definition all the decisions that will define the study are made, this step is probably the most important one in the LCA (Baumann and Tillman, 2004).

5.2 Inventory analysis

The inventory analysis includes creating a more specified model of the system, usually in the form of a flow chart, in accordance to the details determined during the goal and scope definition (Baumann and Tillman, 2004; European Commission, 2010; Goedkoop et al., 2016). The flow chart can be seen as an incomplete mass and energy balance for the system where only the environmentally relevant flows are included and quantified (Baumann and Tillman, 2004). Which processes that are included depend on the system boundary which in turn has an impact on the final result. When deciding on the system boundary, allocation issues can appear for example when a process included generates two or more products but only one of them is of relevance for the studied system. According to the ISO standard for an LCA, allocation should primary be avoided by instead using system expansion (European Commission, 2010). Secondary, if system expansion not is feasible, allocation should be done based on energy, mass or economic correlations (European Commission, 2010). When studying emerging technologies or new products, system expansion when possible with exclusion of irrelevant steps is a recommended method (Hospido et al., 2010; Hetherington et al., 2014).

The inventory analysis is the most demanding and time consuming step as it is here all the data collection and calculations take place (European Commission, 2010; Goedkoop et al., 2016). Data that is needed for the LCA can be divided into two groups; foreground and background data (Goedkoop et al., 2016). Background data is the type of data that is not specific for the studied system and normally includes e.g. electricity and heat production, production of materials and transport, this data can be found in databases (European Commission, 2010). Foreground data on the other hand, is normally the
kind of data that needs to be collected. This is data that describes the studied system and therefore needs to be on a more specific level than found in databases or data for processes or material which are not found in databases at all (European Commission, 2010). Data that for one system is defined as either background or foreground data, can be defined as the other one in another system (European Commission, 2010). The quality of the data can be one of the main sources for uncertainties in an LCA and the more foreground data that can be collected and used, the more correct and robust is the LCA (Baumann and Tillman, 2004; European Commission, 2010; Goedkoop et al., 2016). However, data collection is, as mentioned, a time-consuming process and therefore background data can be used. When using background data, it is important to do so with caution and to remember that this can cause uncertainties in the result since this type of data normally is generalised. When it comes to new and emerging technologies, processes or products, the uncertainties around data and data quality is usually higher than in other cases (Hetherington et al., 2014). The reason for this is that the foreground data usually is collected from lab or pilot scaled trials which lead to poor quality data and sometimes completely missing data (Hetherington et al., 2014). Hetherington et al., (2014) explains that the newer the technology, the more uncertainties in the data, even though it is collected at the source. According to that article, pilot scale is the next best step after industrial scale when it comes to the certainty of the data. However, they also mention that the data can include significant uncertainties since an up-scaling from pilot scale to commercial scale can change the inputs and outputs substantially, something that Hospido et al., (2010) also mentions. One way of identifying how and if the uncertainties affect the result is to do sensitivity analysis (Baumann and Tillman, 2004; European Commission, 2010; Goedkoop et al., 2016).

5.3 Impact assessment

The impact assessment aims at translating the environmental loads quantified in the inventory analysis to the potential environmental impact related to human health, natural environment and resource depletion (European Commission, 2010). The word potential implies that the results from the analysis should not be seen as predictions of the actual environmental impact but rather the potential impact (European Commission, 2010). The impact assessment includes four steps; Classification, Characterization, Normalization and Weighing, of which the first two are mandatory and the last two are optional according to the ISO standard for LCA (European Commission, 2010). In the classification step the results from the inventory analysis are classified in different impact categories according to the substances potential environmental effect (Goedkoop et al., 2016). The characterization step is explained below in section 5.3.1. The normalization step aims at converting the indicator result for each impact category to a more comprehensive one by relating it to a reference situation (European Commission, 2010). The reference situation is normally based on a country’s or citizen’s impact in the relevant category (European Commission, 2010), however it is a choice in the performer’s hand. The normalized result is calculated by dividing the indicator result with the reference situation. Weighing is done by multiplying the indicator result for each impact category with a category specific weighing factor and is used when an aggregated result from all impact categories is desired (European Commission, 2010). The weighing factors represent the importance of the impact categories relatively each other based on scientific expertise, political or other value-based considerations (European Commission, 2010). The factors are therefore subjective and weighing should not be done when the LCA is intended for public use according to the ISO standard (Goedkoop et al., 2016). The guidelines from the ISO standard within the impact assessment area is general and rather unspecific (Hauschild et al., 2013), for example which impact categories that should be included in an LCA and how the substances are classified is no specified in the guidelines. This has led to the development of many different impact assessment methodologies. Between the methodologies, the way the impact assessment is executed differ which impact in the final result for the LCA.
5.3.1 Characterization step

The characterization step uses substance-specific characterization factors to express all results within an impact category in the same unit, allowing an aggregated result within each impact category (Goedkoop et al., 2016; Henryson, Hansson and Sundberg, 2018). In the early development of the impact assessment methods, and still in some methods today, the characterization factor equals the equivalency factor and simply convert different substances to be expressed in the same unit, e.g. CO₂-equivalents for global warming (Henryson, Hansson and Sundberg, 2018). Further research and development in the area have led to insights that the actual impact of different substances depends on rather complicated natural processes and the sensitivity of the receiving environment (Henryson, Hansson and Sundberg, 2018). However, since LCA traditionally is a site-generic tool, the characterization factors in most impact assessment methodologies are also site-generic (Hauschild, 2006). For site-dependent impact categories, for example eutrophication, this could have a huge impact on the final result (Hauschild, 2006). Whereas for site-generic impact categories, for example global warming, the point of emission does not really matter for the environmental impact, hence a site-dependent factor would not make a significant difference in the result.

5.4 Limitations

Even though life cycle assessment is a widely used and accepted tool for environmental analysis of products, processes or services, the tool of course has its limitations. Finnvveden (2000) means that the limitations mainly affect the conclusions that can be drawn from an LCA and mentions three main limitations; Not all environmental impacts are considered, Uncertainties and the Weighing step cannot be objectively determined. The first limitation mentioned refers to the fact that a life cycle assessment cannot cover all environmental problems. Even though one of the strengths of LCA is that it allows an integrated analysis of more than one environmental problem (Baumann and Tillman, 2004), all environmental aspects cannot be covered. One part of this limitation origin in the lack of data connected to the different impact categories and another part is connected to the complexity of the categories. When it comes to new sectors, for example the aqua culture sector, the traditional impact categories is not adapted and furthermore other impact categories could be of interest (Pelletier et al., 2007; Henriksson et al., 2012). In addition, Woods et al., (2016) mean that the LCA tool originally is developed for land-based activities with a focus on terrestrial and fresh water ecosystems. Still today, the focus on marine ecosystems is lacking and only two of the existing impact categories are relevant for assessing the impact on marine environments; marine eutrophication and marine ecotoxicity (Woods et al., 2016). This means that development of the tool with higher data coverage and adapted impact categories can reduce this limitation, however, the complexity of some categories will make it impossible to fill all data gaps (Finnveden, 2000). The second limitation mentioned concerns the uncertainties in the system. As mentioned before, one uncertainty is connected to the quality of the data. With higher data quality and data closer to the studied system, the robustness of the analysis is increased. The methodological choices and system boundary also significantly affect the result and is classified as uncertainties according to Finnvveden (2000), something that also is mentioned as important considerations when analysing aqua culture systems (Pelletier et al., 2007; Henriksson et al., 2012). Because of the definitions and choices made during the Goal and Scope definition, every context of every LCA is different and therefore comparison should be done with caution. Furthermore, those specifications make it incorrect to generalise the result from an LCA. The last limitation is that the weighing step cannot be done objectively but instead, as mentioned in section 5.3, is based on scientific expertise, political or other value-based considerations. The weighing step is not mandatory, but for decision makers to draw conclusions and base decisions on the LCA it is helpful to have done weighing in order to create a fully aggregated result. Despite the limitations of an LCA, it is an important and valuable tool for assessing environmental performance of products,
processes or services in a transparent way. Similar to Finnveden (2000), the authors of this study find that the limitations mainly affect the conclusions that can be drawn from the result and mean that if the limitations, what they are affected by and how they affect the result are understood, the result can be very useful.
6 Previous research

Life cycle assessment has been implemented in many sectors and the usage and coverage of the tool is constantly growing. Only recently has the tool started to be implemented within the aquaculture sector, this is mainly due to the recently fast growing of the sector in combination with a higher interest and awareness of sustainability (Irribarren, 2010; Samuel-Fitwi et al., 2013). As mentioned above, new sectors and assessing impact on the marine environment in particular is a limitation of the tool until the data coverage is expanded and developed. Studies on how LCA can be used within the aquaculture and to assess impact on marine environments show that even though some interesting impact categories are missing, the tool is useful and suitable (Pelletier et al., 2007; Irribarren, 2010; Henriksson et al., 2012). Previous life cycle assessments on aquaculture mainly focus on fish or mussels farmed for human consumption where species, technique and type of fish meal are investigated (Irribarren, 2010; Randau, 2012). When it comes to blue mussels as an environmental measure, the research has mainly focused on testing, proving and discussing the nutrient reduction potential and other environmental benefits of the mussels themselves, hence not including the management of the farm or the equipment needed (Edebo et al., 2000; Sanchez et al., 2004; Lindahl, 2012; Baltic EcoMussel project, 2013; Petersen et al., 2014). Several studies have also investigated the cost-effectiveness of blue mussel farms as a tool for mitigating eutrophication and comparing it to conventional nutrient reduction methods (Sanchez et al., 2004; Gren, Lindahl and Lindqvist, 2009; Stadmark and Conley, 2011; Lindahl, 2012; Baltic EcoMussel project, 2013; Petersen et al., 2014). Studies on the suitability of mussel farming in the Baltic Sea have also been done, showing that there are many suitable places along the coast but that the conditions, for example salinity, currents and predators, but also the farming technique have a major impact on the effectiveness of the farm (Lindahl and Lovén, 2008; Ek Henning and Åslund, 2012; Lindahl, 2012; Baltic EcoMussel project, 2013). The same studies also show that the mussels in the Baltic Sea need two instead of one years to become fully grown and only grow to a smaller size compared to mussels in seas with higher salinity. For this reason, the blue mussels are not suitable for human consumption and therefore investigation on other areas of use were of interest. Several studies investigate if mussel meal as replacement of fish meal in feed can be produced (Jönsson, 2009; Jönsson and Elwinger, 2009; Lindahl, 2012; Vidaković, 2015; Musselfeed, 2018). They all conclude that it is not only possible in respect to content of nutrients, amino and fatty acid, protein and unwanted substances but also that many animals actually prefer feed based on mussels. Furthermore, the mussel meal have a positive impact on the eggs from laying hen. Nordell (2010) show that the meat fraction of blue mussels can be used for biogas production and Biototal (2010) investigate the potential of the digestate as bio-fertilizer. The conclusion is that the nutrient content is rather low but no limits of unwanted substances (e.g. heavy metals) are exceeded and thus the digestate from mussels are allowed as bio-fertilizer. The suitability of blue mussels as fertilizer have also been investigated, however, the studies show high nutrient losses of especially nitrogen (Edebo et al., 2000; Olrog and Christensson, 2008; Olrog et al., 2008; Spångberg, Jönsson and Tidåker, 2013). Furthermore, no trials that completely follow the Swedish regulations have been done. Within this area, Spångberg, Jönsson and Tidåker (2013) did a life cycle assessment on a mussel farm in Kalmar when using the mussels as fertilizer and also comparing different ways of composting the mussels. They also compared the system of mussel farm combined with composting them and using as fertilizer with a conventional system consisting of a waste water treatment plant in combination with mineral fertilizer. In that study they used plant available nitrogen as functional unit and the addressed the impact categories eutrophication, acidification, use of total and non-renewable primary energy and global warming potential. They found that the way of composting the mussels have an impact on the nitrogen losses and thus the nutrient content in the finished fertilizer. Furthermore, they concluded that it is important to consider the multiple functions
mussel farming in combination with production of fertilizer has (nutrient removal, fertilizing value and liming effect) to do a proper assessment and comparison with other similar systems.

The gap in the literature the authors of this study sees concerns further life cycle assessments on mussel farms in the Baltic Sea which have the primary function as an environmental measure. In order to investigate the efficiency of mussel farms as a mitigation tool for eutrophication the activities and material needed for managing of the farm needs to be included in such analysis. Furthermore, the authors found a gap in the previous research concerning studies which include and compare different mussel products in an environmental assessment of mussel farms in the Baltic Sea.
7 Method

In this chapter the overall strategy and method for this study is explained followed by a more detailed description of each step in the method.

The objective and research questions of this study are developed from the premises explained earlier in section 1.1 and is, as a recap from before; “to evaluate the net nutrient reduction in the Baltic Sea of farmed blue mussels including the production of the different mussel products mussel meal, biogas, and compost, in comparison to the systems’ contribution to climate change”. This can be translated into studying a blue mussel farm in the Baltic Sea through its whole life cycle. As earlier explained (see chapter 5) one appropriate and widely used methodology for quantifying environmental impact over a product’s or process’s lifecycle is life cycle analysis (LCA) and is therefore a suitable approach of this study. The methodological choice for this study is supported by LCA’s proved ability to provide the aquaculture industry with transparency and accountability within the sustainability area (Iribarren, Maria Teresa Moreira and Feijoo, 2010). Due to this, LCA has become more frequently used in the aquaculture sector (Henriksson et al., 2012). However, as with all methodologies, LCA has its limitations and aspects that need to be accounted for when analysing the result, those are partly enhanced because of the new sector and technology studied in this LCA. Those limitations are covered on a general level in section 5.4 and on a specific level connected to the studied system when the system is introduced in more detail.

The method for this study is based on the general LCA methodology, further explained above in chapter 5, and contains of four main steps which run parallel with a literature review, see Figure 3. Firstly, the scenarios for the study were developed from the Goal and Scope Definition and the system boundaries were set. The second step was to collect all the relevant data, which was done both by personal contact and by literature research. The next step was the modelling of the life cycle, where the Impact Assessment is included together with the Sensitivity Analysis to investigate the robustness of our model and assumptions. The last step was analysis and discussion of the results. As mentioned, parallel to these steps, a literature review has been done to deepen our knowledge and anchor our study in the theory that already exists. Below, the execution of each step is explained in more detail.

![Figure 3. Illustration of the methodology used in this study, which is based on the general LCA methodology. The method contains of four main steps; Scenarios, Data collection, Modelling and Analysis & Discussion. Parallel to these main steps a literature review was done.](image-url)
7.1 Scenarios

The life cycle of a blue mussel farm in the Baltic Sea is the one studied in this LCA. The primary function, in accordance with the objective of this study, of the mussel farm is to reduce the amount of nutrients in the Baltic Sea to help mitigate the eutrophication. The functional unit refers to the nutrient reduction from the mussels and the reference flow to the weight of mussels needed for the functional unit, those are presented below.

**Functional unit:** Reduction of 11 kg nitrogen and 1,1 kg phosphorous.

**Reference flow:** 1 tonne biomass of blue mussels including the shells.

For the reference flow, the assumption that the mussels contain 1,1 % nitrogen and 0,11 % phosphorous is used which is based on earlier studies on blue mussels from farms in Östergötland (Ek Henning and Åslund, 2012). The nutrient reduction of one harvest depends of the size of the harvest, which in turn depends on the size and the location of the farm among other things. Because of this, we have decided to refer to the reference flow instead of the functional unit throughout this study. This makes it possible to relate the result to a specific farm by linear up-scaling.

The life cycle is divided into four separate scenarios created to answer the two different research questions, see Figure 4. Scenario 1 – Mussel farm directly reflects the first research question and studies the life cycle from a “cradle-to-gate” perspective. This perspective results in that the life cycle stops as soon as the mussels are harvested, and therefore this scenario only includes the mussel farm. The start, “cradle”, of the life cycle is when the fuzzy ropes where the mussels can grow on is placed in the water and the end, “gate”, is when the mussels are harvested. To answer the second research question, the life cycle was expanded to a “cradle-to-grave” perspective which means that the handling of the mussels after harvest also is included. The harvested mussels are in this study seen as a waste from the mussel farm and the production of the different products then becomes waste handling, or even valorisation since the waste is processed into different products to increase the value. As mentioned, there are three possible usages for the mussels; Mussel Meal, Biogas and Compost, also called valorisation possibilities. Each valorisation possibility is combined with the mussel farm and transportation from the farm to the production site and compose a scenario.

Scenario 2 – Mussel meal includes the mussel farm in combination with production of mussel meal, Scenario 3 – Biogas includes the mussel farm in combination with production of biogas and Scenario 4 – Compost includes the mussel farm in combination with production of compost. By including the valorisation of the harvested mussels, the life cycle of the mussel farm is taken all the way to the “grave”. The usage of the produced products, as in production of feed from the mussel meal, combustion of biogas or spreading of biofertilizer and compost, is not included in this study. The reason for this is that the life cycle reflects the mussel farm, and the usage of the products produced from the harvested mussels when considered as waste from the farm is assumed to not be directly connected to the farm. Furthermore, the “cradle-to-grave” perspective in an LCA normally cut the life cycle with the waste handling (Baumann and Tillman, 2004). The production and disposal of capital goods, such as machinery needed for the production of the different mussel products, are in general not taken into account in this LCA in accordance to the second order in the ISO standards for LCA (Goedkoop et al., 2016).
The overall constellations of the different scenarios and the system boundaries are shown in Figure 4. Each scenario is built up by main processes (see grey boxes) and need different inputs in form of material (blue boxes) and energy (green boxes). The orange ovals represent a product already on the market which the possible mussel product could replace. The “avoided products” is a result from the chosen way of modelling, further explained in section 7.3. A detailed explanation of the scenarios, their main processes and the inputs is found in the following chapter 8.

Figure 4. Illustration of the studied system and the overall constellation of the scenarios where the dotted lines show the system boundaries for each scenario. Scenario 1 – Mussel farm (purple dotted line) consists of the mussel farm only. Scenario 2 – Mussel meal (green dotted line), Scenario 3 – Biogas (blue dotted line) and Scenario 4 – Compost (red dotted line) consists of the mussel farm in combination with one of the valorisation possibilities and they all also include the transport from the farm to the production site. The grey boxes in scenarios represent the main processes and the orange ovals represents the avoided products in each scenario. The blue boxes represent the material input and the green boxes represent the energy input for each scenario.

7.2 Data collection

The data collection was done both through personal contact and by a literature review. The aim throughout the data collection was to collect the data as close to the source as possible, meaning e.g. from the mussel farm in St. Annas archipelago and from an industry producing mussel meal. This resulted in that personal contact was preferred. The people who have been contacted for data collection is presented in Table 1. Through the BBG-project and our mentor Lena Tasse at Region Östergötland we got in contact with people involved in mussel farming (especially the farm in St. Anna) and mussel meal production. Additional contacts within the area were identified through the literature review and the initial contacts. For data within the biogas area we contacted Tekniska Verken because of their experience with using mussels as a substrate for biogas production. However, first hand data directly from the source has not always been available or reachable and to fill those gaps estimations or generic data from databases have instead been used. Since many of the included processes in this studied life cycle is still in a trial phase and in pilot or small scale, there exist uncertainties in the data, those are more specified under each scenario explanation in chapter 8.
Table 1. Presentation of the persons who have been contacted during the data collection for this study. In the table their name, which company they work for and their position in that company as well as which form of contact that has been used is presented.

<table>
<thead>
<tr>
<th>Name</th>
<th>Company</th>
<th>Position at company</th>
<th>Form of contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lena Tasse</td>
<td>Region Östergötland</td>
<td>Project manager</td>
<td>Personal meeting/Email</td>
</tr>
<tr>
<td>Mats Emilsson</td>
<td>Mussel farmer for St. Anna farm</td>
<td>Telephone</td>
<td>Telephone</td>
</tr>
<tr>
<td>Sverre Aarønen</td>
<td>Nofima</td>
<td>Production manager</td>
<td>Email</td>
</tr>
<tr>
<td>Ola Palm</td>
<td>RISE Agrifood and Bioscience</td>
<td>Section manager</td>
<td>Email</td>
</tr>
<tr>
<td>Erik Nordell</td>
<td>Tekniska Verken AB</td>
<td>Development Engineer at department Biogas R&amp;D</td>
<td>Email</td>
</tr>
</tbody>
</table>

For the background processes, such as transport, energy, and production of materials included in the system, inventory databases have been used. The databases that have been used in this study are “Ecoinvent 3”, “Agri-footprint” and “LCA food DK”, see Table 3 to Table 7 to see which process that comes from which database. The reason for using multiple databases is that none includes all processes needed. Ecoinvent is a well-known, globally used database and call themselves the leading database for LCA-modelling (Ecoinvent, 2018). For this study the Ecoinvent was compiled in October 2017. Although Ecoinvent is a big and an accepted database (Goedkoop et al., 2016) it does not include all background processes needed for modeling the system analyzed in this LCA. Therefore complementary and more field-specific databases such as agriculture footprint and LCA food DK have been used. Agri-footprint is a high-quality database focused on the agriculture and food sector (Durlinger et al., 2017). The Agri-footprint database was compiled in March 2017 for this study. LCA food DK is a database covering basic food products from Denmark (Nielsen et al., 2003). This database is specific for Denmark and not updated since 2007 (Nielsen et al., 2003), and therefore it has been used carefully and only when Ecoinvent or Agri-footprint have not been sufficient.

7.3 Modelling

For the modelling of the life cycle in this study, the LCA tool Simapro was used with the version 8.4.0.0 Classroom Multi user. Simapro was created by PRé Sustainability (PRé Sustainability, 2018). In the modelling, partially system expansion was used. As mentioned in section 7.1, the usage of the produced mussel products is not included in this study, but it is included what the produced products can replace in form of “avoided products”, which is why system expansion is only done partially. This is only done for Scenario 2 – Mussel meal, Scenario 3 – Biogas and Scenario 4 – Compost, and to see what different avoided products that are included in what scenario see Figure 6 and Figure 8 to Figure 10 in the chapter 8. The reason why the avoided products are included is because both we and our mentor at Region Östergötland thought it would be interesting to show how it could impact the result to include avoided products. That the system expansion is not done fully is because the life cycle reflects the mussel farm, and the usage of the products produced from the waste (the harvested mussels) from the farm is assumed to not be directly connected to the farm which goes for the avoided products as well. Since the avoided products are only included with production of them, and not the usage, this could have an impact on the result which is discussed later on.

7.3.1 Impact Assessment

Hauschild et al. (2013) performed a screening of all the existing impact assessment methods to identify best practice, from a European perspective, in the 15 most commonly used impact categories. The result were summarized in a new method, ILCD (European Comission, 2011), which is the method chosen as a base for the impact assessment in this study. The ILCD method is not used straight off but modified to better suit this study’s goal and scope. The ILCD method includes 15 impact categories,
however, only two have been included in this LCA. The included impact categories are aquatic eutrophication and climate change. Eutrophication is chosen because the mussels are grown to mitigate the eutrophication in the Baltic Sea and climate change because the impact on the climate is today a very current subject and is frequently discussed. Aquatic eutrophication is expressed in N-equivalents, in this impact category some changes have been made in the classification and characterization, see the following section 7.3.1.1. Climate change is measured in global warming potential (GWP) with a 100-year timeframe and expressed in CO$_2$-equivalents. The impact assessment within this category is based on the IPCC model. IPCC is the most up-to-date and scientifically robust model available and comes with three different timeframes; 20-year, 100-year, and 500-year (European Commission, 2011). The 100-year timeframe is used in most policy documents (European Commission, 2011), therefore it can be assumed to be the most accepted and is for that reason chosen in this study.

As mentioned in section 5.3 normalization is done to relate the results to a reference situation. Normalization is therefore done to simplify the interpretation of the results and make it relatable. The normalization in this study is done with an average European citizen as the reference scenario in both impact categories. The reference scenarios are based on which emissions and how much of each substance one citizen, on average, releases in one year (Benini et al., 2014). This has been calculated by dividing the total emissions from the EU-27 countries with the current population in the same year. The normalization factor for the different impact categories is then the corresponding emissions expressed in equivalents of one substance, for example, CO$_2$-equivalents for climate change. Since the mussels needs two growth periods before they can be harvested, the life cycle of the mussels is assumed to be two years. So the normalization factor is multiplied by two to also correspond to two years’ worth emissions. For climate change, a more updated number than the existing one in the ILCD-method in SimaPro was found and therefore used (Eurostat, 2018). For eutrophication, a more recent number was not found and the one in the ILCD-method was used but calculated from P-equivalents to N-equivalents. The reference scenarios for eutrophication and climate change respectively was 55,22 kg N-equivalents and 14,2 tonnes CO$_2$-equivalents.

The authors have decided not to do the weighing step in this LCA but instead leave this to the reader if a fully aggregated result is desired.

7.3.1.1 Characterization factor
ILCD uses the ReCiPe 2008 method for the aquatic eutrophication impact category, a method that uses characterizations factors adapted to European water bodies on average, but not a specific receiving water body (European Commission, 2011). The environmental impact in the aquatic eutrophication impact category is measured as a substance’s potential to increase the biomass growth (Seppälä, Knuuttila and Silvo, 2004), therefore the most important factor for this impact category is the limiting nutrient in the receiving environment (European Commission, 2011). The ILCD-method has separate impact categories for eutrophication in freshwater (mostly P-limited) and marine (mostly N-limited) environments (European Commission, 2011). This results in one category which includes all N compounds and another one with all the P compounds, expressed in different units. Since the Baltic Sea is said to be both N- and P-limited, emissions of both nutrients need to be taken into account when estimating the eutrophication. Because of the different units, the result from the two impact categories of interest (freshwater and marine eutrophication) cannot simply be added to each other. To the authors best knowledge, no method which includes an impact category for aquatic eutrophication separately from terrestrial eutrophication considers both phosphorus and nitrogen compounds in the same impact category. Therefore, the authors decided to modify the chosen method to better reflect the Baltic Sea. The aim was to merge the two aquatic impact categories into
one and be able to express the combined result in the same unit. For this, the characterization factors for phosphorous compounds (from the freshwater eutrophication impact category) were converted from being expressed in P-equivalents to N-equivalents by using the equivalence factors, and a “Baltic Sea” eutrophication impact category was made. To calculate the equivalence factors the Redfield-relation was used, which is based on an average composition of algae biomass according to the relation C:N:P=106:16:1 (Klöpffer and Grahl, 2014). The Redfield-relation is commonly used to calculate equivalence factors for eutrophicating substances (Klöpffer and Grahl, 2014). It does not take the regional composition of the water bodies into account (Klöpffer and Grahl, 2014). With the help of the Redfield-relation and Klöpffer and Grahl (2014) three different equations were used to calculate the equivalent factors for the phosphorus compounds.

\[ P: m(N) = \frac{m(P) \cdot M(N) \cdot 16}{M(P)} \text{ [kg N – equivalents/kg P]} \] (1)

\[ PO_4^{3-}: m(N) = \frac{m(PO_4^{3-}) \cdot M(N) \cdot 16}{M(PO_4^{3-})} \text{ [kg N – equivalents/kg PO_4^{3-}]} \] (2)

\[ BOD: m(N) = \frac{m(O_2) \cdot M(N) \cdot 16}{M(O_2) \cdot 138} \text{ [kg N – equivalents/kg BOD]} \] (3)

All three equations are based on equations from Klöpffer and Grahl (2014) and expresses compounds that have an impact on eutrophication in N-equivalents.

Where m is the mass of the substance and M is the molar mass of the substance. 16 comes from the Redfield-relation and is used because the molar ratio of P/N is 1/16. BOD, biological oxygen demand, is also included in our method since these substances consume oxygen when they degrade and therefore contributes to eutrophication (Naturvårdsverket, 2016). Since BOD consumes oxygen it is calculated with the chemical formula of O₂ (Klöpffer and Grahl, 2014). The calculated equivalence factors that come from equation (1), (2) and (3) are presented in Table 2 together with the characterization factor from ILCD’s freshwater eutrophication category and the characterization factor used in our new category after calculations.

**Table 2. Presentation of the substances that are recalculated to N-equivalents and inserted into ILCD’s marine eutrophication method, each substance’s characterization factor used in this analysis and the numbers used to calculate them.**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphorus (Water)</td>
<td>P</td>
<td>1</td>
<td>7,24</td>
<td>7,24</td>
</tr>
<tr>
<td>Phosphate (Water)</td>
<td>PO₄³⁻</td>
<td>0,33</td>
<td>2,36</td>
<td>2,36</td>
</tr>
<tr>
<td>Phosphorus (Soil)</td>
<td>P</td>
<td>1</td>
<td>7,24</td>
<td>7,24</td>
</tr>
<tr>
<td>Phosphate (Soil)</td>
<td>PO₄³⁻</td>
<td>0,33</td>
<td>2,36</td>
<td>2,36</td>
</tr>
<tr>
<td>Phosphorus total (Water)</td>
<td>P-tot</td>
<td>1</td>
<td>7,24</td>
<td>7,24</td>
</tr>
<tr>
<td>Phosphorus total (Soil)</td>
<td>P-tot</td>
<td>1</td>
<td>7,24</td>
<td>7,24</td>
</tr>
<tr>
<td>Fertilizer P-component</td>
<td>P</td>
<td>0,053</td>
<td>7,24</td>
<td>0,38**</td>
</tr>
<tr>
<td>Manure P-component</td>
<td>P</td>
<td>0,05</td>
<td>7,24</td>
<td>0,36**</td>
</tr>
<tr>
<td>BOD, biological oxygen demand</td>
<td>O₂</td>
<td>-</td>
<td>0,051 [kg N eq/kg O₂]</td>
<td>0,051</td>
</tr>
</tbody>
</table>

* From the “Freshwater eutrophication” impact category in the ILCD-method.

** Calculated by multiplying the characterization factor from the “Freshwater eutrophication” impact category and equivalence factor.
7.4 Analysis and discussion

The result from the life cycle assessment of the different scenarios is presented graphically and analysed. For numerical presentation of the results, see Table A1 to Table A3 in Appendix. First comes the result to answer each of the two research questions where Scenario 1 – Mussel farm correspond to research question 1 and Scenario 2 – Mussel meal, Scenario 3 – Biogas and Scenario 4 – Compost answer to research question 2. Within each research question the result from the two sensitivity analysis is presented. The sensitivity analysis is done to show how different assumptions, in this case two, can affect the result. After that, a normalized result is presented to put the result in a perspective. For the presentation of the result the life cycle is divided into 8 stages; Mussels, Material farm, Energy use farm, Transport, Material production, Energy use production, Avoided products and Compost emissions, see Figure 5. “Mussels” include the nutrient reduction from the mussels and is therefore only visible in the eutrophication impact category. “Material farm” and “Energy farm” includes the input needed for the mussel farm. “Transport” includes transportation of the harvested mussels from the farm to the production site. “Material production” and “Energy use production” includes the input needed to produce the different mussel products. “Avoided products” includes for the avoided impact for not producing the replaced products. “Compost emissions” includes the emissions during composting and is therefore only applicable in the composting scenario. Since Scenario 1 – Mussel farm only includes the mussel farm, this result only includes the first three stages; Mussels, Material farm and Energy farm.

The result is presented for each of the two included impact categories; Eutrophication and Climate Change and both per reference flow (1 tonne mussels) and per 1 harvest of the St. Anna farm (75.5 tonne mussels). The last presentation option is to visualize the impact from 1 harvest of a farm and to show that the result is linear scalable relative the weight of the mussels.

![Figure 5. Illustration of the 8 stages the life cycle is divided into when presenting the result and which scenario contains which stage. The 8 stages are; Mussels, Material farm, Energy use farm, Transport, Material production, Energy use production, Avoided products and Compost emissions.](image)
8 Detailed description of the scenarios

In this chapter we will take a closer look on each of the scenarios and the included processes will be explained in more detail. The data and parameters used in the modelling is also presented. The tables, Table 3, Table 4, Table 6 and Table 8, with the input and output data in section 8.1 to 8.4 in this chapter is based on 1 harvest, ergo 75,5 tonne mussels. For values based on the reference flow, 1 tonne mussels, the values in the tables can be divided with 75,5 since it is linearly scaled. After each scenario is described, a section with source of errors connected to the scenario is presented to show the uncertainties and explain how the results are affected.

8.1 Scenario 1 – Mussel farm

Scenario 1 – Mussel farm is built up by the mussel farm and the system boundaries for this scenario is set directly after the harvesting of the mussels. Figure 6 illustrates the processes, material and energy included within the system boundaries for this scenario.

The technique used for the farm in St. Anna, Östergötland, Sweden is called long line system (Emilsson pers. com., 2018). This technique contains lines that float on the surface with the help of buoys, “floating lines” and are anchored in the bottom to a cement block in each end. From each rope on the surface, several plastic lines (called fuzzy ropes) hang and on these, the mussel larvae will attach and grow, see Figure 7. In St. Anna there are 16 “floating lines” á 150 meters, each with 150 pieces of “fuzzy ropes” á 10 meters attached to them. This gives a total of 24 000 meters “fuzzy rope” for the mussels to grow on in the farm. There is a total of 500 buoys holding up the farm and 32 concrete blocks á 3 tonnes anchoring the farm. In December 2017, 3,5 “floating lines” which contained 15,5 tonnes of mussels was harvested from the farm in St. Anna. The fisherman responsible for the farm and harvest, Mats Emilsson, estimates that there is around 60 tonne left (Emilsson pers. com., 2018). That gives a value of 3-3,2 kg mussels per meter “fuzzy rope” and a total predicted harvest of 75,5 tonne mussels. For supervision of the farm, Mats Emilsson uses a smaller boat and during harvest he uses a floating working platform (similar to a barge) which he built himself. The boat, platform and the hydraulic used for the harvesting run on petrol as fuel (Emilsson pers. com., 2018). Estimations on the fuel consumption were made by Mats Emilsson, which was that the boat uses 37,5 litres of fuel and the hydraulic 10 litres of fuel for the harvest per 6 hours. SimaPro did not have a default process which combusted petrol in a boat engine, and therefore a fishing vessel that uses diesel was used in
the modeling. To take into account the difference between the two fuels we used the energy content in petrol and diesel to convert the amount of petrol used to the amount of diesel needed. For the different materials that are used for the ropes, buoys, concrete blocks and the harvesting equipment in the farm, the production of the virgin material is included. However, the production of the actual equipment is not included in this study, since this information was not found. For example, this means that the production of the plastic for the “mussel lines” is included but the production of the lines is excluded.

![Figure 7. Illustration of the long line technique for mussel farming, which is the technique used in St. Anna, Östergötland, Sweden. The black lines are the ones holding the farm together (“floating lines”). Those are attached to buoys (red circles) to stay afloat as well as cement blocks on the sea floor to be held in place. The grey lines hanging from the black lines are plastic bands which the mussel larvae attach to and grow big on (fuzzy ropes).](image)

Analysis from previous studies on farmed mussels in the archipelago of Östergötland shows that the percentage meat (wet weight) of the whole biomass (wet weight) differs depending on the conditions, and therefore the location, of the farm site and ranges from 30 % - 50 % (Ek Henning and Åslund, 2012). Ek Henning and Åslund also showed that mussels from the archipelago of Östergötland on average contain 1,1 % nitrogen and 0,11 % phosphorus calculated on the whole mussel, including the shell. In our study, an average of 40 % meat fraction is used in the calculations. This means that the 75,5 tonne of mussels from the farm in St. Anna removes a total of 830,5 kg nitrogen and 83,05 kg phosphorus.

Most of the data about the farm in St. Anna comes from the mussel farmer Mats Emilsson. However, some of this data has not been measured but instead estimated by him based on his experience from managing the farm. This means that the data could be overestimated or underestimated and thus lead to uncertainties. Furthermore, this farm is in a trial phase and the management of it and the equipment used is not optimized which also could lead to uncertainties. When it comes to the equipment for the farm, information from the retailer about e.g. material, size or weight has been used to complement missing information. Since the mussels in the Baltic Sea needs 2 growth periods before they can be harvested, the timeframe for this LCA is 2 years. However, to include that the material lasts longer than 2 years and can be used again, an assumed lifetime of 10 years for the material was used which is estimated by Emilsson (pers. com., 2018). This means that the material that is needed for the farm was divided with a factor 5 to get 10 years lifespan. The inputs and outputs for the farm are showed in Table 3.
Table 3. Presentation of the inputs and outputs used in Scenario 1 – Mussel farm. The table presents which material/process that is referred to, which material or process in Simapro the data is taken from and what value and unit that is used. The column “calculated with” presents which numbers that have been used if the value is based on any calculations. “Reference” presents where the value or numbers for calculations have been taken from.

<table>
<thead>
<tr>
<th>Material/process</th>
<th>Material/data on</th>
<th>Value</th>
<th>Unit</th>
<th>Calculated with</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Produced mussels, the whole weight</td>
<td></td>
<td>75,5</td>
<td>tonne</td>
<td></td>
<td>(Emilsson pers. com., 2018)</td>
</tr>
<tr>
<td>Amount of fuel the boat uses</td>
<td>Fishing vessel, diesel combusted in (LCA Food DK)</td>
<td>1926</td>
<td>liter</td>
<td>15,87 liter/hour and 4 liter/hour for supervision. From petrol to diesel energy content is used.</td>
<td>(SPBI, 2016; Emilsson pers. com., 2018; Honda Marine, 2018)</td>
</tr>
<tr>
<td>Plastic is used for the fuzzy ropes</td>
<td>Polypropylene, granulate (GLO) (Ecoinvent)</td>
<td>1,13</td>
<td>tonne</td>
<td>Weight of 236 g/m</td>
<td>(Donaghys, 2014)</td>
</tr>
<tr>
<td>Concrete used for the anchor blocks</td>
<td>Concrete block (GLO) (Ecoinvent)</td>
<td>19,2</td>
<td>tonne</td>
<td>3 tonne/unit, 32 units</td>
<td>(Emilsson pers. com., 2018)</td>
</tr>
<tr>
<td>Plastic is used for the buoys</td>
<td>Polyethylene, high density, granulate (GLO) (Ecoinvent)</td>
<td>0,5</td>
<td>tonne</td>
<td>5 kg/unit, 500 units</td>
<td>(Emilsson pers. com., 2018; JFC Marine, 2018)</td>
</tr>
<tr>
<td>Plastic used in the “floating lines”</td>
<td>Polypropylene, granulate (GLO) (Ecoinvent)</td>
<td>395</td>
<td>kg</td>
<td>Density of 930 kg/m³. Thickness of 28 mm (floating lines) and 32 mm (ropes between the floating lines and the concrete blocks).</td>
<td>(De Rosa and Auriemma, 2006; Emilsson pers. com., 2018)</td>
</tr>
<tr>
<td>Steel needed for the harvesting equipment</td>
<td>Steel, chromium steel 18/8 (GLO) (Ecoinvent)</td>
<td>120</td>
<td>kg</td>
<td></td>
<td>(Emilsson pers. com., 2018)</td>
</tr>
</tbody>
</table>

8.1.1 Source of errors
Fishing vessel was chosen because it was the only smaller boat transportation available in Simapro. However, it uses diesel as fuel instead of petrol that we knew was used in reality, and since combustion of diesel and petrol differs in emissions this could have an impact of the result compared to reality. There was no process in Simapro that combusted petrol or diesel without being included in another process, so this fishing vessel process was the closest process to the reality. One reason the fishing vessel was chosen over another transportation that wasn’t on water is because vehicles on water don’t have the same regulations as road vehicles. Road vehicles have more reduction of nitrogen oxides than boats and a higher efficiency. Another thing in favor to the fishing vessel and the fact that it is a transportation on water is that the emissions occur close to the water and therefore may have more effect on for instance eutrophication in water because of nitrogen oxides emissions. Nitrogen oxides affect aquatic eutrophication when the emissions dissolve in the water (Hansson and Elding, 2018), which logically means that the closer the emissions are to the water the easier it can be dissolved. This means that the fishing vessel, despite not having the right fuel consumption, gives a better model of the reality and its effects. The calculations on how much fuel the boat for the farm uses is made from many assumptions. For the bigger boat the numbers for the fuel consumption are more certain because they are estimated from the mussel farmer based on how much fuel that was used during the harvest in the end of 2017. For the smaller boat we only got the information about
what type of engine it had. To calculate the fuel consumption, we looked up the type of engine in a brochure and then assumed two different engine speeds (rpm) and got the fuel consumption from that, together with a time from the mussel farmer. Since the fuel consumption is a fossil fuel it has a high impact mainly in climate change but also on eutrophication which means that these assumptions could affect the results.

Other uncertainties in this study is that for the mussel farm there are a few bigger assumptions made. For example, the density of the polypropylene plastic is taken from a source, but the density can vary depending on what type of polypropylene plastic it is and how it has been treated. For the fuzzy ropes it can also vary in weight depending on what kind of fuzzy ropes that is used, and here we did not have that detailed information so one kind was chosen from their website. Both the plastic density and the weight of the fuzzy ropes have an impact on how much plastics is needed in the farm and have an impact on the result. It is shown in the result that the material for the farm have a high impact in climate change and plastic stands for a big part of that. The results of this study are also affected since only the production of the virgin material and not the production of the actual products is included in this study. An inclusion of production of different products of this virgin material would increase the impact results since another step in the life cycle would be included. The lifespan of the material is in this study assumed to be 10 years, ergo to be used 5 times, which also affects the results in both impact categories. Since the result is presented after a lifespan of 2 years a shorter lifespan of the materials would mean a higher impact in the result of 2 years and a longer lifespan would mean a lower impact. In this case it is assumed that the materials would last all the way over these 10 years, but in reality this might not be the case. In reality one might need to exchange some of the material during this 10 years if materials are negatively exposed and the durability thereby is affected negatively. The results from the farm is also depended on how much mussels that is produced and here the results are only partly based on real measurements. In the end of 2017 they farmed 15,5 tonnes from St. Anna's farm and then how much mussels that are left was estimated from the mussel farmer which means that it can be different. This affects how much nutrients can be removed, which affects the results in the eutrophication category, but also how much materials are needed per tonne mussels.
8.2 Scenario 2 – Mussel meal

Scenario 2 – Mussel meal is built up by the mussel farm in combination with production of mussel meal and it also includes the transportation of the mussels from the farm to the production site, see Figure 8.

Blue mussels farmed in the archipelago of Östergötland do not contain amounts of organic pollutants that exceed the limits for being able to be used as feed (Ek Henning and Åslund, 2012). The mussels from the St. Anna farm are therefore assumed to be allowed for mussel meal production. The production of mussel meal is in this study based on how a company in Norway is producing mussel meal, which is through hydrolysis (Palm pers. com., 2018). In this process the mussels are first mixed with water, with a 50/50 relation, then 1 % enzymes is added. The whole mixture is then put in a hydrolysis tanker and heated to around 55 degrees for about 120 minutes and heated to over 90 degrees for about 10 minutes (Palm, 2018). With the enzymes and the heat, the protein from the mussels is “melted” out from the shells, resulting in that the meat and the shells are separated (Palm, 2018). Then the “meat slurry” is put through a separator to increase the dry matter content (Palm, 2018). After that the meat is spray-dried at around 62 degrees, in order to convert it into powder (Palm, 2018). Producing mussel meal is a developing industry and the technique or the processes are not yet optimized. For instance, the company that performed this mussel meal production noticed that it was more difficult than anticipated to spray-dry the mussels and therefore the low temperature was needed (Palm, 2018). The final result gave an exchange ratio for which 32,7 kg of mussels were needed to produce 1 kg of mussel meal (Aarønen pers. com., 2018). The production process is electricity and steam demanding, however, the steam used in the process in this particular case is bought from Nordic Pharma which produces the steam from excess heat (Aarønen pers. com., 2018; Nordic Pharma, 2018). The primary heat is produced from clean and renewable fuel and hydropower (Aarønen pers. com., 2018; Nordic Pharma, 2018). The assumption is therefore that the steam production included in this study does not have any emissions. In a hydrolysis process, the shell and meat from the mussels are separated, which means that the mussel shells are a byproduct. Since the shells contain high amounts of calcium they can, according to Kollberg and Lindahl (2004), be used as lime. One tonne of mussels gives 300 kg of lime (Kollberg and Lindahl, 2004). To include in the result that the shells can be used for something else and thereby replace lime, avoided products is used.
which gives the result a negative impact to the total score. Mussel meal can replace fish meal, which also is included in the study in form of avoided production of fish meal.

All data for the mussel meal production comes from a trial production in small scale. All inputs and outputs for this production were measured and therefore the data we have received is reliable but specific for their production. However, since it is a small-scale production and the first time they have tried to produce mussel meal, the production is not optimized and does not reflect a big scale, commercialized production. The inputs and outputs for the mussel meal production are showed in Table 4.

Table 4. Presentation of the inputs and outputs used in Scenario 2 – Mussel meal. The table presents which material/process that is referred to, which material or process in Simapro the data is taken from and what value and unit that is used. The column “calculated with” presents which numbers that have been used if the value is based on any calculations. “Reference” presents where the value or numbers for calculations have been taken from.

<table>
<thead>
<tr>
<th>Material/process</th>
<th>Material/data on</th>
<th>Value</th>
<th>Unit</th>
<th>Calculated with</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Produced mussel meal</td>
<td></td>
<td>2 311</td>
<td>kg</td>
<td></td>
<td>(Aarønen pers. com., 2018)</td>
</tr>
<tr>
<td>Electricity needed to produce mussel meal</td>
<td>Electricity, medium voltage (NO) (Ecoinvent)</td>
<td>201,6</td>
<td>MWh</td>
<td></td>
<td>(Aarønen pers. com., 2018)</td>
</tr>
<tr>
<td>Steam needed to produce mussel meal*</td>
<td></td>
<td>466,7</td>
<td>MWh</td>
<td>24500 kg steam and specific enthalpy 2706,2 kJ/kg at 120°C for saturated steam</td>
<td>(Beaton, 1986; Aarønen pers. com., 2018)</td>
</tr>
<tr>
<td>Water needed to produce mussel meal</td>
<td>Water, deionized, from tap water, at user (Europe without Switzerland) (Ecoinvent)</td>
<td>4 441</td>
<td>m³</td>
<td></td>
<td>(Aarønen pers. com., 2018)</td>
</tr>
<tr>
<td>Sodium hydroxide used to produce mussel meal</td>
<td>Sodium hydroxide (50% NaOH), production mix/RER Mass (Agri-footprint)</td>
<td>9,7</td>
<td>tonne</td>
<td></td>
<td>(Aarønen pers. com., 2018)</td>
</tr>
<tr>
<td>Avoided fish meal production</td>
<td>Fish meal, from fish meal and oil production, at plant/NO Mass (Agri-footprint)</td>
<td>-2 311</td>
<td>kg</td>
<td>One to one relation fish meal and mussel meal.</td>
<td>(Jönsson, 2009)</td>
</tr>
<tr>
<td>Avoided lime production due to the high lime content in the shells</td>
<td>Limestone, crushed, for mill (RoW) (Ecoinvent)</td>
<td>-22,7</td>
<td>tonne</td>
<td>1 tonne mussels gives 300 kg lime</td>
<td>(Kollberg and Lindahl, 2004)</td>
</tr>
<tr>
<td>Transport distance times weight of mussels for production of mussel meal</td>
<td>Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling (GLO) (Ecoinvent)</td>
<td>133 182</td>
<td>tkm</td>
<td></td>
<td>Google maps</td>
</tr>
</tbody>
</table>

* This steam is assumed to have zero emissions and therefore not included in the modeling in Simapro.
8.2.1 Source of errors

One source of error in this scenario is the fact that the production was a trial run for this company. This means that numbers used in the calculations for production of mussel meal is based on a real production, but that production was a first try for the company and therefore not fully optimized. This means that the numbers on electricity use or materials used in the production could either be higher or lower which influences the result. The ratio between how much mussels are needed to produce a certain amount of mussel meal could also be different since the production was a trial. How much mussel meal that is produced is not showed in the result as less energy or material needed, but in the avoided products. Depending on how much mussel meal is produced, the amount of fish meal that can be avoided changes, since mussel meal can replace fish meal with a 1 to 1 ratio.

8.3 Scenario 3 – Biogas

Scenario 3 – Biogas is built up by the mussel farm in combination with anaerobic digestion to produce biogas and biofertilizer and it also includes the transportation of the mussels from the farm to the production site, see Figure 9.

The meat fraction of a blue mussel can be digested to biogas, however, the shell fraction cannot. Prior to entering the digestion chamber the two fractions therefore need to be separated. Tekniska Verken in Linköping uses a cyclone separator in their pretreatment which is installed to prevent unwanted material to enter the digestion chamber (Nordell pers. com., 2018). The function of the cyclone for blue mussels was tested in December 2017 when Tekniska Verken received the first harvest of blue mussels from the St. Anna farm (Nordell pers. com., 2018). Nordell confirms that it went well to receive the mussels in the biogas production plant, both in the cyclone separator and the digestion chamber. The mussels were co-digested with other substrates and therefore the shell fraction is assumed to be mixed with other waste from the cyclone separator, and thus cannot replace lime. Since Tekniska Verken in Linköping can handle the mussels without large problems, and the proximity to the farm in St. Anna, the blue mussels in this study are assumed to be sent to Tekniska Verken in Linköping for digestion to biogas. In 2010, Tekniska Verken tested the methane potential of mussel meat in a laboratory scale (Nordell, 2010). In our LCA, a mean value of the results from the laboratory tests is used, 34,923 Nm³/tonne. It is also assumed that the total meat fraction (40 %) reaches the digestion chamber, hence there is no waste of the meat in the pretreatment. The biogas is then assumed to replace fossil fuels and avoided products are again applied. The avoided products are in this case production of petrol, not the combustion (usage) of it, only the production. The digestate that is left from the digestion is assumed to be used as biofertilizer to replace mineral fertilizer. Tests on blue mussels from the archipelago of St. Anna have shown that the amount of organic pollutants (e.g. heavy metals) are within the limits and the mussels are therefore allowed to be used as fertilizer.
(Ek Henning and Åslund, 2012). However, because of the high water content in the mussels the nutrient content in the digestate is rather low relative to the mass (Biototal, 2010). Furthermore, the nutrients are only partly preserved during the anaerobic digestion. The same happens regardless of which substrate that is used but depending on the substrate and the digestion process the nutrient loss can vary. To calculate the nutrient content in the digestate, average numbers on the nitrogen loss during anaerobic digestion have been used and the phosphorus is assumed to have no losses. The last part is because the anaerobic digestion takes place in a closed chamber with no leakage to water or the ground and unlike nitrogen, phosphorus does not exist in gaseous form (see chapter 3) and therefore no losses to the air can occur. After the digestion it is also assumed that there is 75 % plant available nitrogen in the biofertilizer (Linder, 2010), see Table 5 for calculations of the nutrient content in biofertilizer. By using the digestate as biofertilizer a circular flow of the nutrients are created, and production of mineral fertilizer can be avoided. If the mussels are digested with other substrates which will be the case in Linköping, the digestate will become more nutrient rich (Biototal, 2010).

Table 5. Table of the nutrient numbers used when calculating to nutrient content in the biofertilizer after the biogas production.

<table>
<thead>
<tr>
<th>Nutrient content mussels [kg]</th>
<th>Nitrogen</th>
<th>Phosphorus</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nutrient losses [%]</td>
<td>830,5</td>
<td>83,05</td>
<td>(Möller, 2015)</td>
</tr>
<tr>
<td>Total nutrient content biofertilizer [kg]</td>
<td>735</td>
<td>83,05</td>
<td>(Möller, 2015)</td>
</tr>
<tr>
<td>Plant available [% of total nutrient content]</td>
<td>75</td>
<td>100</td>
<td>(Linder, 2010)</td>
</tr>
<tr>
<td>Plant available content [kg]</td>
<td>551,2</td>
<td>83,05</td>
<td>(Möller, 2015)</td>
</tr>
</tbody>
</table>

The primary idea was to use data from Linköping’s biogas production. However, this was not possible since they do not measure the production specifically and to get those number an energy audit must be made, which does not fit within this study. Instead, the data on electricity and heat comes from a study where an energy survey was made at the biogas production plant at Kungsängens gård near Uppsala, see Table 6. This does not reflect the proper energy need for producing biogas from blue mussels at Tekniska verken since every biogas plant is different and the energy use varies between different productions sites. However, it does give us an idea of what the energy need could be like for biogas production. The energy used for upgrading the biogas was not included in that study and those numbers had to be collected elsewhere. The biogas plant in Linköping uses the amino scrubber technique for the upgrading of biogas and data on its energy use is taken from a report by Swedish Gas Technology Center (today Energiforsk) (Bauer et al., 2013). Every biogas plant has leakage of methane during the production, but in this study the leakage is not included in the calculations. The inputs and outputs for the biogas production are shown in Table 6.
Table 6. Presentation of the inputs and outputs used in Scenario 3 – Biogas. The table presents which material/process that is referred to, which material or process in Simapro the data is taken from and what value and unit that is used. The column “calculated with” presents which numbers that have been used if the value is based on any calculations. “Reference” presents where the value or numbers for calculations have been taken from.

<table>
<thead>
<tr>
<th>Material/process</th>
<th>Material/data on</th>
<th>Value</th>
<th>Unit</th>
<th>Calculated with</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Produced biogas</td>
<td></td>
<td>712,7</td>
<td>m³</td>
<td>34,923 Nm³/tonne meat fraction</td>
<td>(Nordell, 2010)</td>
</tr>
<tr>
<td>Produced biofertilizer from biogas production</td>
<td></td>
<td>27,2</td>
<td>tonne</td>
<td>40 % meat fraction and left is 90 % of input</td>
<td>(Biototal, 2010; Nordell, 2018)</td>
</tr>
<tr>
<td>Heat needed to produce biogas</td>
<td>Heat, for reuse in municipal waste incineration only (SE) treatment of municipal solid waste, incineration (Ecoinvent)</td>
<td>13,2</td>
<td>MWh</td>
<td>169,8 kWh/tonne plus 0,55 kWh/m³ for upgrading</td>
<td>(Andersson, 2011; Bauer et al., 2013)</td>
</tr>
<tr>
<td>Electricity needed to produce biogas</td>
<td>Electricity, medium voltage (SE) (Ecoinvent)</td>
<td>11,6</td>
<td>MWh</td>
<td>152 kWh/tonne plus 0,14 kWh/m³ for upgrading</td>
<td>(Andersson, 2011; Bauer et al., 2013)</td>
</tr>
<tr>
<td>Avoided nitrogen fertilizer from biogas production</td>
<td>Nitrogen fertiliser, as N (GLO) (Ecoinvent)</td>
<td>-549</td>
<td>kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avoided phosphate fertilizer from biogas production</td>
<td>Phosphate fertiliser, as P2O5 (GLO) (Ecoinvent)</td>
<td>-190</td>
<td>kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avoided petrol production from biogas production</td>
<td>Petrol, 5% ethanol by volume from biomass (GLO) (Ecoinvent)</td>
<td>-476</td>
<td>kg</td>
<td>1 Nm³ biogas weighs 0,75 kg. 1 kg vehicle gas replaces 1,5 liter petrol. Density 752 kg/m³</td>
<td>(SPBI, 2016; Svensk biogas, 2018)</td>
</tr>
<tr>
<td>Transport distance times weight of mussels for production of biogas</td>
<td>Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling (GLO) (Ecoinvent)</td>
<td>5,874</td>
<td>tkm</td>
<td>From St. Anna archipelago to Åby Västergård 3 Linköping</td>
<td>Google maps</td>
</tr>
</tbody>
</table>

8.3.1 Source of errors
For the biogas production, it is assumed to be produced in Linköping, Östergötland, but the energy consumption is taken from another production facility. The energy use can vary significantly between different production facilities which means that this affects the results, but we don’t know if it would be a lower or higher energy consumption if we got the energy use from the facility in Linköping. As for the methane potential, the tests are done in a lab which means better conditions and thereby better exchange. These tests show the maximum biogas potential, but in a more industrial process, the methane potential is usually lower, around 70-90 % of the maximum potential (Nordell, 2010). So, the fact that the test is done in a lab and not a more industrial process is partly considered, but it could still differ more than what it is calculated for. As for the calculations with the nutrient content after the digestion a general number of nitrogen losses in the digestion is used. This could also vary dependent on facility, what substrate is digested and how the digestion happens. How much of the
nitrogen left that is plant available could also vary between different facilities, digestion processes and what substrate that is digested and for the calculations in this study a general number is also used. The phosphorus losses are in this study assumed to be zero, which is based on the fact that phosphorus does not exist in a gaseous form. However, there could still be a small amount of phosphorus losses in the digester. All this affects the calculations for the nutrient content is the digestate which in turn affects how much mineral fertilizer that can be replaced. Since the mineral fertilizer is an avoided product in this scenario, a lower amount of nutrients means a higher total impact and a higher amount of nutrients means a lower total impact. As for the affection of the results on not including methane leakage from the biogas plant it could have a substantial impact on the climate change. The methane leakage also affects how much upgraded biogas that can be produced and in turn how much fossil fuel that can be avoided.

8.4 Scenario 4 – Compost

Scenario 4 – Compost is built up by the mussel farm in combination with composting of the mussels and it also includes the transportation of the mussels from the farm to the production site, see Figure 10.

Tests on blue mussels from the archipelago of St. Anna have shown that the amount of organic pollutants (e.g. heavy metals) are within the limits and is therefore allowed to be used as compost (Ek Henning and Åslund, 2012). In a trial composting of blue mussel, the highest temperature that was reached during compost was 65 degrees (Olrog et al., 2008), which is not high enough according to Swedish regulations. The temperature needs to reach a higher temperature to kill the bacteria in the compost. No data from studies or contacts have been found from composting of mussels performed according to Swedish regulations, and therefore the data in this study is based on the trial composting of blue mussels. Although it is not done according to the regulations it still gives information about the emissions during the composting process and the nutrient content in the final compost. In trials the mussels are mixed with straw to create a better compost with a ratio of 50 kg straw per 1 tonne of mussels, the mixture is then windrow composted (Spångberg, Jönsson and Tidåker, 2013). The mixture was stored for approximately 6 months where the compost was turned 4 times with an interval of 5 weeks. It is for this study assumed that the composting process happens in a controlled environment and on an impenetrable bottom, so the nutrient losses only occur in form of air emissions. 58 % of the nitrogen content in the substrate prior to composting are lost as emissions in
form of ammonia, nitrogen gas and dinitrogen oxide during the composting process (Spångberg, Jönsson and Tidåker, 2013). After the composting it is assumed that there is 12,8 % plant available nitrogen in the compost (Olrog and Christensson, 2008). For phosphorus it is assumed to be no losses since it is done in a controlled environment and phosphorus can’t be released as air emissions (see chapter 3). The nutrient content in the final compost in our study is calculated with these numbers for losses but based on the nutrient content in the mussels from the St. Anna farm, see Table 7 for the numbers of the nutrient calculations. The compost is assumed to be used as fertilizer in agriculture which means that mineral fertilizer could be avoided. Since the mussels are composted with their shells, the compost is also assumed to avoid production of lime. Since the shells contain mostly of CaO it has a liming effect on the farmland and lime does not need to be added to the farmland separately as it’s normally done (Spångberg, Jönsson and Tidåker, 2013). The mussels are, after harvesting assumed to be transported to a waste disposal plant in Högbytorp northwest of Stockholm. This facility states on their website that they can handle organic waste and the mussels are therefore assumed to be able to compost there (Ragnsells, 2018). In this study, the spreading of the compost is not included, only the production. The inputs and outputs for the composting are showed in Table 8.

Table 7. Table of the nutrient numbers used when calculating to nutrient content in compost after the compost production.

<table>
<thead>
<tr>
<th>Nutrient content mussels [kg]</th>
<th>Nitrogen</th>
<th>Phosphorus</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nutrient losses [%]</td>
<td>830,5</td>
<td>83,05</td>
<td>(Spångberg, Jönsson and Tidåker, 2013)</td>
</tr>
<tr>
<td>Total nutrient content compost [kg]</td>
<td>348,8</td>
<td>83,05</td>
<td></td>
</tr>
<tr>
<td>Plant available [% of total nutrient content]</td>
<td>12,8</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Plant available content [kg]</td>
<td>44,6</td>
<td>83,05</td>
<td></td>
</tr>
</tbody>
</table>

Table 8. Presentation of the inputs and outputs used in Scenario 4 – Compost. The table presents which material/process that is referred to, which material or process in Simapro the data is taken from and what value and unit that is used. The column “calculated with” presents which numbers that have been used if the value is based on any calculations. “Reference” presents where the value or numbers for calculations have been taken from.

<table>
<thead>
<tr>
<th>Material/process</th>
<th>Material/data on</th>
<th>Value</th>
<th>Unit</th>
<th>Calculated with</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel used to turn the compost during the process</td>
<td>Diesel, burned in agricultural machinery (GLO) (Ecoinvent)</td>
<td>703,2</td>
<td>MJ</td>
<td>0,26 liters per tonne</td>
<td>(Spångberg, Jönsson and Tidåker, 2013)</td>
</tr>
<tr>
<td>Avoided lime due to the lime content of the mussel shells</td>
<td>Limestone, crushed, for mill (RoW) (Ecoinvent)</td>
<td>-15,5</td>
<td>tonne</td>
<td>225 kg CaO-eq/1097 kg mussels</td>
<td>(Spångberg, Jönsson and Tidåker, 2013)</td>
</tr>
<tr>
<td>Avoided nitrogen fertilizer from compost production</td>
<td>Nitrogen fertilizer, as N [GLO] (Ecoinvent)</td>
<td>-45</td>
<td>kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avoided phosphate fertilizer from compost production</td>
<td>Phosphate fertiliser, as P2O5 [GLO] (Ecoinvent)</td>
<td>-190</td>
<td>kg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amount of straw mixed with the mussels in the composting process</td>
<td>Straw [AU] wheat production (Ecoinvent)</td>
<td>3775</td>
<td>kg</td>
<td>50 kg per tonne mussels</td>
<td>(Spångberg, Jönsson and Tidåker, 2013)</td>
</tr>
<tr>
<td>Transport distance times weight of mussels for production of compost</td>
<td>Transport, freight, lorry with refrigeration machine, 7,5-16 ton, EURO6, R134a refrigerant, cooling [GLO] (Ecoinvent)</td>
<td>18 649</td>
<td>tkm</td>
<td></td>
<td>(Spångberg, Jönsson and Tidåker, 2013)</td>
</tr>
</tbody>
</table>
8.4.1 Source of errors
The calculations in this scenario that has the largest impact on the results are the calculations related to the nutrient losses. The nutrient losses can vary between productions and depends on the substrate for composting. Since the number in this study comes from a study where the composting is done on mussels, it gives a bit more certainty, but could still vary from time to time. However, the study is only based on one test for composting mussels. Since composting is not done in a closed facility but with an impenetrable bottom, the losses that occurs is to the air. The emissions to the air consists of nitrogen compounds, which could influence both the climate change and the eutrophication. So the results is affected depending on how much losses there are but also how much plant available nitrogen that is left after the composting. The number on how much plant available nitrogen that is left is also based on a study done on mussels, but also with just one test, which gives a certain amount of uncertainty to the result. Since the composting is assumed to happen on an impenetrable bottom, the phosphorus losses are assumed to be zero since there is no gaseous emissions of phosphorus compounds. All this nutrient losses and plant available nitrogen also affects how much mineral fertilizer the compost can replace, which affects the result. Since the mineral fertilizer is an avoided product in this scenario, a lower amount of nutrients means a higher total impact and a higher amount of nutrients means a lower total impact.

8.5 Sensitivity analysis
Sensitivity analyses are done to show how different assumptions influences the results. In this study, the size of the farm and the transportation distance and fuel is assumed to influence the results largely and is therefore chosen for a sensitivity analysis. For analyzing the size of the farm, Scenario 1 – Mussel farm, is analyzed. To also see the improvement the farm can have in the future another fuel for the boat is also considered. More explanation on why and how the sensitivity analyses are made, see the following sections 8.5.1 and 8.5.2

8.5.1 Future development Scenario 1 – Mussel farm
This sensitivity analysis is done to see how future development of the farm would affect the result based on one tonne mussels from the St. Anna farm. Since the results is depending on how large the mussel farm is, this sensitivity analysis was done to see how the size affects the results. Two different developments are studied; a change from a pilot scale mussel farm to an assumed commercial scaled mussel farm and a change from fossil fuel to more environmental friendly fuel. The sensitivity analysis consists of 3 cases; Worst, Modest and Best. Worst is here the same as Scenario 1 – Mussel farm. For the Modest case the mussel farm is scaled up to a more commercial farm and for the Best case the commercial scaled farm is combined with a more environmental friendly boat fuel. The maximum size of the farm the mussel farmer in St. Anna is limited by the harvesting machine (Tasse pers. com., 2018). The harvesting period is assumed by the authors to be limited to the months after the winter and before the growth season has ended which resulted in the months April-July. The reason for the assumption is that the mussel cannot be harvested later than July is because the fuzzy ropes the mussel grow on are placed back directly after harvest for new mussel to attach. If the fuzzy ropes are placed in the water too late, no mussels will be able to attach, and instead other marine animals and algae will start to grow on the fuzzy ropes. With four months harvest period and an assumed workload of five days per week this generated 6 mussels farms exactly as the ones from Scenario 1 – Mussel farm that can be harvested per year. Since the mussels need two growth season, ergo two years, before they can be harvested the maximum size was then doubled. This result in a bigger farm and thus more mussels but also a more even workload and distribution of mussels. This means that in the Modest and the Best cases, a total of 12 Scenario 1 – Mussel farms is assumed to equal one commercial sized farm. Since the harvest is assumed to take place five days a week, no extra
supervision is needed during the harvesting period. For the commercial sized farm, we have instead assumed supervision one time per month in four months and the remaining four months of the year is the winter months when ice might be covering the sea making the farm inaccessible. This has resulted in that the fuel consumption per tonne mussel is different in the Modest and the Best cases compared to the Worst case. The material, on the other hand, except is scaled up linearly (everything steel that is used for the harvesting equipment). How much mussels that can grow and be harvested along with how much nutrients that can be removed is also scaled up linearly. The only difference between the Modest case and the Best case is that in the Best case the boat is assumed to run on electricity instead of fossil fuels. This means that we have calculated how much energy the fuel consumed in the Modest case contains and assumed that the same amount of electricity is needed instead. One of the reasons to choose an electricity boat in the future is because the electricity in Sweden is relatively “green” (mainly based on non-fossil energy sources) which makes it an environmental friendly energy source. Another reason is that an electricity engine does not have any local emissions when used. So, for both the Modest case and the Best case there can be 906 tonnes mussels to harvest, which would mean a removal of 9 966 kg nitrogen and 996,6 kg phosphorus. The inputs for the sensitivity analysis for Scenario 1 – Mussel farm are shown in Table 9.

Table 9. Inputs and outputs for the three cases in sensitivity analysis of Scenario 1 – Mussel farm with numbers presented for both 1 harvest and 1 tonne of mussels.

<table>
<thead>
<tr>
<th></th>
<th>Worst case</th>
<th>Modest case</th>
<th>Best case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Produced mussels, the whole weight [tonne]</td>
<td>75,5 1</td>
<td>906 1</td>
<td>906 1</td>
</tr>
<tr>
<td>Amount of fuel the boat uses [m³]</td>
<td>1,93 0,026</td>
<td>10,32 0,011</td>
<td>-  -</td>
</tr>
<tr>
<td>Plastic is used for the long lines [kg]</td>
<td>1 132,8 15,0</td>
<td>13 593,6 15,0</td>
<td>13 593,6 15,0</td>
</tr>
<tr>
<td>Concrete used for the anchor blocks [tonne]</td>
<td>19,2 0,25</td>
<td>230,4 0,254</td>
<td>230,4 0,25</td>
</tr>
<tr>
<td>Plastic is used for the buoys [kg]</td>
<td>500 6,62</td>
<td>6 000 6,62</td>
<td>6 000 6,62</td>
</tr>
<tr>
<td>Plastic used in the lines that hold up the long lines [kg]</td>
<td>394,54 5,23</td>
<td>4 734,48 5,23</td>
<td>4 734,48 5,23</td>
</tr>
<tr>
<td>Steel needed for the harvesting equipment [kg]</td>
<td>120 1,59</td>
<td>120 0,13</td>
<td>120 0,13</td>
</tr>
<tr>
<td>Electricity for the boat [MWh]</td>
<td>- -</td>
<td>102,7 0,11</td>
<td></td>
</tr>
</tbody>
</table>

8.5.2 Transport variation

Here a sensitivity analysis is done on transportation between the mussel farm and different production sites in Scenario 2 – Mussel meal, Scenario 3 – Biogas and Scenario 4 – Compost. For Scenario 2 – Mussel meal and Scenario 4 – Compost, the location of production was not known and therefore three different locations were chosen to see how the distance affects the result. For Scenario 3 – Biogas the location was known and therefore not varied. Knowing that transportation stands for a significant amount of emissions and thereby a large environmental impact (Naturvårdsverket, 2018), it was also of interest to do a sensitivity analysis on the fuel for the transportation in Scenario 2 – Mussel meal, Scenario 3 – Biogas and Scenario 4 – Compost. The possible locations for each scenario was combined both with fossil fuel and non-fossil fuel and each combination apart from the one used in the reference scenario is called a variation and given a name. The non-fossil fuel used in this analysis is a biodiesel from vegetable oil, mostly produced from rapeseed. The location and fuel that is used in the original result for each scenario is called the
reference scenarios and keeps the scenario name to show that it represents the reference. The transportation sensitivity analysis is done with 1 tonne of mussels and all distances have been calculated with the help of Google maps. In the sections below the variations in each scenario is further explained and the names of the variations together with the inputs are shown in Table 10 to Table 12.

8.5.2.1 Scenario 2 – Mussel meal
Today, no commercial mussel meal producer exists in Europe (Tasse pers. com., 2018) and therefore the actual location to where the mussels will be transported is not known. Three possible production sites in northern Europe have been located and chosen together with Lena Tasse, our mentor and project manager for the mussel farm of St. Anna and analyzed to see how the distance influence the result. Two of those, Tromsø in Norway and Limfjorden in Denmark are industries producing fish meal which have tried to produce small batches of mussel meal. St. Petersburg in Russia has a fish meal industry to where Swedish fishermen today send fish for fish meal (Tasse pers. com., 2018), which is why that is also a possible location site included. The transport starts in the archipelago of St. Anna. To Tromsø and Limfjorden the mussels are being transported with a truck all the way, for Limfjorden this means that the transportation goes by Öresund and the bridge there. For the transportation to St. Petersburg, Russia, the mussels first go by truck to Västervik and then goes by ship all the way to St. Petersburg. Each possible location of the mussel meal production is combined with both fossil fuel and non-fossil fuel and all different variations and their inputs are shown in Table 10.
Table 10. Presentation of the inputs used in the sensitivity analysis for production sites for mussel meal production. The table presents which material/process that is referred to, which material or process in SimaPro the data is taken from and what value and unit that is used. “Variation of Scenario 2 – Mussel meal” refers to the fact that all these transports are connected to Scenario 2 – Mussel meal with different names to separate the different sites and different fuels. The column “calculated with” presents which numbers that have been used if the value is based on any calculations. “Reference” presents where the value or numbers for calculations have been taken from.

<table>
<thead>
<tr>
<th>Variation of Scenario 2 – Mussel meal</th>
<th>Material/process</th>
<th>Material/data on</th>
<th>Value</th>
<th>Unit</th>
<th>Calculated with</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fossil</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 2</td>
<td>Transportation from St. Anna’s farm to Tromsø, Norway</td>
<td>Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling {GLO} (Ecoinvent)</td>
<td>1 764</td>
<td>tkm</td>
<td>1 tonne of mussels</td>
<td>Google maps</td>
</tr>
<tr>
<td>Scenario 2b</td>
<td>Transportation from St. Anna’s farm to Limfjorden, Denmark</td>
<td>Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling {GLO} (Ecoinvent)</td>
<td>900</td>
<td>tkm</td>
<td>1 tonne of mussels</td>
<td>Google maps</td>
</tr>
<tr>
<td>Scenario 2d</td>
<td>Transportation from St. Anna’s farm by truck to Västervik (to St.Petersburg)</td>
<td>Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling {GLO} (Ecoinvent)</td>
<td>103</td>
<td>tkm</td>
<td>1 tonne of mussels</td>
<td>Google maps</td>
</tr>
<tr>
<td>Scenario 2d</td>
<td>Transportation by cargo ship from Västervik to St. Petersburg, Russia</td>
<td>Transport, freight, sea, transoceanic ship with reefer, cooling (GLO) (Ecoinvent)</td>
<td>855</td>
<td>tkm</td>
<td>1 tonne of mussels</td>
<td>Google maps</td>
</tr>
<tr>
<td><strong>Fossil free</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 2a</td>
<td>Transportation from St. Anna’s farm to Tromsø, Norway</td>
<td>Transport, freight, lorry 28 metric ton, vegetable oil methyl ester 100% {GLO}</td>
<td>1 764</td>
<td>tkm</td>
<td>1 tonne of mussels</td>
<td>Google maps</td>
</tr>
<tr>
<td>Scenario 2c</td>
<td>Transportation from St. Anna’s farm to Limfjorden, Denmark</td>
<td>Transport, freight, lorry 28 metric ton, vegetable oil methyl ester 100% {GLO}</td>
<td>900</td>
<td>tkm</td>
<td>1 tonne of mussels</td>
<td>Google maps</td>
</tr>
<tr>
<td>Scenario 2e</td>
<td>Transportation from St. Anna’s farm by truck to Västervik (to St.Petersburg)</td>
<td>Transport, freight, lorry 28 metric ton, vegetable oil methyl ester 100% {GLO}</td>
<td>103</td>
<td>tkm</td>
<td>1 tonne of mussels</td>
<td>Google maps</td>
</tr>
<tr>
<td>Scenario 2e</td>
<td>Transportation by cargo ship from Västervik to St. Petersburg, Russia</td>
<td>Transport, freight, sea, liquefied natural gas {GLO}</td>
<td>855</td>
<td>tkm</td>
<td>1 tonne of mussels</td>
<td>Google maps</td>
</tr>
</tbody>
</table>
8.5.2.2 Scenario 3 – Biogas

Since we know that the mussels would go to Tekniska verken in Linköping if the mussels are used for biogas production, this location is the only possibility included in this study. We know that they can handle the mussels in their production and since the mussels are produced in the region of Östergötland, Region Östergötland would like to use them in Östergötland as well to keep it at a regional level. Since it is kept on a regional level, the transportation distance is also kept short. Which means that the only variation in this scenario is a change from fossil fuel to non-fossil fuel, see Table 11 for the inputs used in the sensitivity analysis in this scenario.

Table 11. Presentation of the inputs used in the sensitivity analysis for production sites for biogas production. The table presents which material/process that is referred to, which material or process in SimaPro the data is taken from and what value and unit that is used. “Variation of Scenario 3” refers to the fact that the transport in Scenario 3 – Biogas is done with different fuels and therefore given different names. The column “calculated with” presents which numbers that have been used if the value is based on any calculations. “Reference” presents where the value or numbers for calculations have been taken from.

<table>
<thead>
<tr>
<th>Variation of Scenario 3</th>
<th>Material/process</th>
<th>Material/data on</th>
<th>Value</th>
<th>Unit</th>
<th>Calculated with</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil</td>
<td>Transportation from St. Anna’s farm to Tekniska verken</td>
<td>Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling (GLO) (Ecoinvent 3)</td>
<td>77,8</td>
<td>tkm</td>
<td>1 tonne of mussels</td>
<td>Google maps</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>Linköping for biogas production</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fossil free</td>
<td>Transportation from St. Anna’s farm to Tekniska verken</td>
<td>Transport, freight, lorry 28 metric ton, vegetable oil methyl ester 100% (GLO)</td>
<td>77,8</td>
<td>tkm</td>
<td>1 tonne of mussels</td>
<td>Google maps</td>
</tr>
<tr>
<td>Scenario 3a</td>
<td>Linköping for biogas production</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

8.5.2.3 Scenario 4 – Compost

The actual site to where the mussels will be sent for composting is not known and therefore it is of interest to see how different possibilities would affect the result. The site used in the reference scenario (Scenario 4 – Compost) is a facility that has a big scale production for compost located in Högbytorp, northwest of Stockholm. Another possibility is to send the mussels to a facility in Kil, located in the region of Värmland near Karlstad. This is an open windrow composting facility (Mewab, 2018). Windrow composting of mussels have been tested in a study by Spångberg, Jönsson and Tidåker (2013) and therefore this site is included as a possibility. The last possibility that is analyzed in this study is to build a new composting facility in the region which is assumed to be placed close to the harbor and the harvested mussels from the St. Anna farm. This possibility is included based on the interest from Region Östergötland to use the mussels within the region if composting is the chosen valorization option (Tasse pers. com., 2018). The transport distance would in this variation be negligible and is therefore set to zero and the construction of the facility is excluded in the analysis. All possible production sites are combined with both fossil fuel and non-fossil fuel and the names of the different variations together with their input are shown in Table 12.
Table 12. Presentation of the inputs used in the sensitivity analysis for production sites for compost production. The table presents which material/process that is referred to, which material or process in SimaPro the data is taken from and what value and unit that is used. “Variation of Scenario 4” refers to the fact that all these transports are connected to Scenario 4 – Compost with different names to separate the different sites and different fuels. The column “calculated with” presents which numbers that have been used if the value is based on any calculations. “Reference” presents where the value or numbers for calculations have been taken from.

<table>
<thead>
<tr>
<th>Variation of Scenario 4</th>
<th>Material/process</th>
<th>Material/data on</th>
<th>Value</th>
<th>Unit</th>
<th>Calculated with</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fossil</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 4</td>
<td>Transportation from St. Anna’s farm to <strong>Högbytorp</strong> for compost production</td>
<td>Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling {GLO} (Ecoinvent 3)</td>
<td>247</td>
<td>tkm</td>
<td>1 tonne of mussels</td>
<td>Google maps</td>
</tr>
<tr>
<td>Scenario 4b</td>
<td>Transportation from St. Anna’s farm to <strong>Kil</strong> for compost production</td>
<td>Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, cooling {GLO} (Ecoinvent 3)</td>
<td>288</td>
<td>tkm</td>
<td>1 tonne of mussels</td>
<td>Google maps</td>
</tr>
<tr>
<td><strong>Fossil free</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scenario 4a</td>
<td>Transportation from St. Anna’s farm to <strong>Högbytorp</strong> for compost production</td>
<td>Transport, freight, lorry 28 metric ton, vegetable oil methyl ester 100% {GLO}</td>
<td>247</td>
<td>tkm</td>
<td>1 tonne of mussels</td>
<td>Google maps</td>
</tr>
<tr>
<td>Scenario 4c</td>
<td>Transportation from St. Anna’s farm to <strong>Kil</strong> for compost production</td>
<td>Transport, freight, lorry 28 metric ton, vegetable oil methyl ester 100% {GLO}</td>
<td>288</td>
<td>tkm</td>
<td>1 tonne of mussels</td>
<td>Google maps</td>
</tr>
<tr>
<td>Scenario 4d</td>
<td><strong>Zero transportation</strong> due to new facility</td>
<td></td>
<td>0</td>
<td>tkm</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
9 Result and analysis

In this chapter the result from the LCA will be presented, both in the eutrophication and the climate change category. The result will be presented per reference flow, 1 tonne mussels, and per one harvest from St. Anna which equals to 75,5 tonne mussels. Lastly, the results from the sensitivity analyses will be presented, as well as the result from the normalization.

9.1 Research question 1

In order to answer the first research question, “What is the net reduction of nitrogen and phosphorus and the contribution to climate change of farmed blue mussels in the Baltic Sea?”, Scenario 1 – Mussel farm was created. In Scenario 1 – Mussel farm, the life cycle of the mussel farm is defined to “the gate” which corresponds to directly after the harvest of the mussels. This means that only the mussel farm is included in the analysis. For a visual recap of the 8 stages in the life cycle see Figure 5.

The result for Scenario 1 – Mussel farm shows that this scenario gives a reduction in the eutrophication impact category even when considering the material and energy needed for managing the farm, see Figure 11. This reduction is due to the nutrient uptake from the mussels (the blue part of the stack). The nutrient reduction from the mussels can vary between farming techniques and location and thus impact the result. The material and energy use within the farm (orange and grey parts of the stack respectively) have a eutrophicating impact, however, this impact is insignificantly small compared to the nutrient reduction from the mussels, and thus the net impact is negative. The impact from the energy use in the farm is higher than from the material, which is due to the emissions of nitrogen oxides from the combustion of fossil fuel in the boat. The small impact from the material for the farm comes from the energy use within the production of the material.

![Figure 11](image-url)

*Figure 11. The result for Scenario 1 – Mussel farm show a net reduction of eutrophication even when including the material and energy for the management of the farm. This result is for 1 tonne of mussels (the reference flow) and presented with the unit kg N-equivalents. The blue part of the stack, “mussels”, corresponds to the nutrient reduction from the mussels. The orange part of the stack, “material farm” corresponds to the impact from the production of the plastic, concrete and steel needed for the equipment for the farm. The grey part of the stack, “energy use farm” corresponds to the impact from combustion of fossil fuel in the boat.*
Scenario 1 – Mussel farm has an impact in regards of the climate change impact category, as seen in Figure 12. “Mussels” is not present in this impact category since this stage corresponds to the nutrient reduction of the mussels which does not affect climate change. The energy use and the material needed for the farm both have impact on climate change and stands for approximately half of the total impact each. The impact from the energy use originates from the emissions of carbon dioxide released during the combustion of fossil fuels in the boat. The impact from the material primary comes from the plastic used in the fuzzy ropes, “floating lines” and buoys, which have an impact in climate change both because energy is needed in the production and because it is produced from oil which is a fossil resource. The concrete used in the concrete blocks also has an impact on climate change although this is smaller than the one from plastic. For this material it is the high energy need in the production that stands for most of the impact and the reason it is smaller than the impact for plastic is mainly because a lot less of concrete is used compared to plastic (see Table 3). Steel, which is the last material used in the mussel farm, only have a small contribution compared to the other materials which is mainly because only a small amount is used in the farm.

![Climate change, kg CO₂-eq.](image)

Figure 12. Within the climate change impact category, the result show that Scenario 1 – Mussel farm have an impact. This result is for 1 tonne of mussels (the reference flow) and presented with the unit kg CO₂-equivalents. The blue part of the stack, “mussels”, corresponds to the nutrient reduction from the mussels and is therefore not present within this category. The orange part of the stack, “material farm” corresponds to the impact from the production of the plastic, concrete and steel needed for the equipment for the farm. The grey part of the stack, “energy use farm” corresponds to the impact from combustion of fossil fuel in the boat.

Figure 13 show that there is a net reduction of eutrophication for Scenario 1 – Mussel farm when one harvest, which equals to 75,5 tonne mussels, instead of one tonne is studied. This is natural since the result is linearly scaled.
For one harvest, which equals to 75.5 tonne mussels, there is a net reduction of eutrophication for Scenario 1 – Mussel farm even when including the material and energy for management of the farm. This result is presented with the unit kg N-equivalents. The blue part of the stack, “mussels”, corresponds to the nutrient reduction from the mussels. The orange part of the stack, “material farm” corresponds to the impact from the production of the plastic, concrete and steel needed for the equipment for the farm. The grey part of the stack, “energy use farm” corresponds to the impact from combustion of fossil fuel in the boat.

Figure 14 show that Scenario 1 – Mussel farm have an impact on climate change when one harvest, which equals to 75.5 tonne mussels, instead of one tonne is studied. This comes naturally from the linear scaling from 1 to 75.5 tonne mussels.

The result for one harvest, equal to 75.5 tonnes of mussels, shows that Scenario 1 – Mussel farm contribute to climate change. The result is presented with the unit tonne CO₂-equivalents. The blue part of the stack, “mussels”, corresponds to the nutrient reduction from the mussels and is therefore not present within this category. The orange part of the stack, “material farm” corresponds to the impact from the production of the plastic, concrete and steel needed for the equipment for the farm. The grey part of the stack, “energy use farm” corresponds to the impact from combustion of fossil fuel in the boat.
9.1.1 Sensitivity analysis – Future development Scenario 1 – Mussel farm

Since the mussel farm in St. Anna, which this study is based on, still is in trial phase and in pilot scale it is of interest to study how an upscaling to commercial scale would affect the result. Furthermore, it is of interest to study how the result would be affected to a change from fossil fuel for the boat to a more environmental fuel, in this study the choice fell on electricity. These changes to the farm is what is analysed in this sensitivity analysis by the comparison of three cases; Worst, Modest and Best. The Worst case corresponds to the farm analysed in Scenario 1 – Mussel meal, which represents how the farm is today; pilot scale. In the Modest case the farm is scaled to an assumed commercial scale. The Best case is as the Modest case but with electricity instead of petrol as fuel for the boat. The sensitivity analysis is based on the reference flow; 1 tonne mussels.

The result in Figure 15 shows that there is an insignificant change in the result within the eutrophication impact category between the three cases and all three cases have a net reduction. The Modest case is slightly better than the Worst case, and the Best case is even better. The magnitude of the impact from “Material farm”, is small in all three cases and practically unchanged between the cases. The latter is because most of the material (everything except for the steel) is scaled linearly between the pilot scaled and the commercial scaled farms. This means that the material use per tonne mussel is practically the same for a pilot scaled and a commercial scaled farm. The only change is the amount of steel used, of which the production does not have a major impact in eutrophication and therefore does not affect the magnitude of the impact. The magnitude of the impact from “Energy use farm” on the other hand, is reduced with just above 50% between the Worst and the Modest cases, and with almost 90% between the Modest and the Best case. Since the magnitude of the impact in the Worst case is small, the reductions in absolute numbers are also small even though the reduction in percentage is relatively high, which is why the net result only is slightly affected by the reductions. The reduction in “Energy use farm” between the Worst and the Modest cases is a result of a more energy efficient farm which in turn is a result from the commercial scale in comparison to the pilot scale that is today. The reduction between the Modest case and the Best case is due to the change of fuel for the boat from fossil fuel to electricity. Since the electricity in Sweden, in majority, is fossil-free, the emissions from electricity production is less compared to the combustion of petrol directly in the boat.
Figure 15. Comparison of three different cases in Scenario 1 – Mussel farm show minimal difference within the eutrophication impact category, and all cases have a net reduction. The result is presented for 1 tonne mussels (the reference flow) and in the unit kg N-equivalents. The Worst case corresponds to the reference scenario and thus represent the mussel farm as it is today, in pilot scale. In the Modest case, the mussel farm is scaled to commercial scale and in the Best case the farm is scaled to commercial scale and the boat is assumed to run on electricity instead of fossil fuel. The blue part of the stack, “mussels”, corresponds to the nutrient reduction from the mussels. The orange part of the stack, “material farm” corresponds to the impact from the production of the plastic, concrete and steel needed for the equipment for the farm. The grey part of the stack, “energy use farm” corresponds to the impact from combustion of fossil fuel in the boat.

A distinct reduction of the total climate change impact can be seen between all cases where the Worst case has the highest impact and the Best case has the lowest impact, see Figure 16. The impact from “Material farm” is only slightly reduced from Worst case to Modest case and unchanged between Modest case and Best case. The latter is because the size of the farm and thus the material inputs are the same between the Modest and the Best cases. The small reduction between the Worst case and the Modest case is a result from the upscaling of the farm. The reason the reduction per tonne mussels is not bigger is because most of the material (everything except the steel for the harvest equipment) is scaled linearly relative the weight of the mussels. This means that the material use for all materials except the steel is the same per tonne mussels regardless the size of the farm. The main reason for the reduction of climate change impact between the cases is instead seen in “Energy use farm”. Between the Worst and the Modest cases, the reduction is due to an increased energy efficiency of the farm which comes from the upscaling from pilot scale to commercial scale. In the commercial scale the farm is assumed to be harvested every weekday during four months and supervision is assumed to be done in combination with harvesting, thus no extra supervision is needed during those harvesting months. Furthermore, the supervision done during the none harvesting months is assumed to use the same amount of fuel for the pilot scaled farm and the commercial scaled farm. This is because the boat trip between the harbour and the farm is unchanged in both cases and is the part of the supervision that uses most of the fuel assumed for one supervision. The number of supervisions has also been reduced from one time per week in the Worst case to one time per month in the Modest and Best cases. Summarized, this leads to less fuel used per tonne mussels which means a more energy efficient farm and gives less contribution to climate change. The reduction of the impact in climate change between the Modest and the Best cases is due to the change of fuel from fossil fuel to electricity. Swedish electricity mix is used in the Best case which is mainly based on non-fossil energy and therefore has less impact than the fossil fuel used in the Worst and Modest cases.
Figure 16. Comparison of three different cases within Scenario 1 – Mussel farm for the climate change impact category show that the impact from “Energy use” reduces from the Worst case to the Best case. The result is presented for 1 tonne mussels (the reference flow) and in the unit kg CO₂-equivalents. In the sensitivity analysis three cases; Worst, Modest and Best, are compared. The Worst case corresponds to the reference scenario and thus represent the mussel farm as it is today, in pilot scale. In the Modest case, the mussel farm is scaled to commercial scale and in the Best case the farm is scaled to commercial scale and the boat is assumed to run on electricity instead of fossil fuel. The blue part of the stack, “mussels”, corresponds to the nutrient reduction from the mussels and is therefore not present within this category. The orange part of the stack, “material farm” corresponds to the impact from the production of the plastic, concrete and steel needed for the equipment for the farm. The grey part of the stack, “energy use farm” corresponds to the impact from combustion of fossil fuel in the boat.

9.2 Research question 2

To answer the second research question, “How is the net reduction of nitrogen and phosphorus and the contribution to climate change of the different mussel products biogas, mussel meal and compost compared to each other?”, the life cycle of the mussel farm was extended to the “cradle-to-grave” perspective to also include valorisation of the harvested mussels. Three valorisation possibilities are studied in this LCA and thus three different scenarios were created; Scenario 2 – Mussel meal, Scenario 3 – Biogas and Scenario 4 – Compost. All three scenarios include the mussel farm (Scenario 1 – Mussel farm) in combination with the production of one of the three mussel products and the transportation of the mussels from the farm to the production site, see Figure 5 for a recap of the 8 stages in the life cycle.

In the eutrophication impact category, all three scenarios give a reduction in eutrophication, see Figure 17, which is why the y-axis in the figure is inverted. Scenario 3 – Biogas has the biggest reduction in eutrophication, so the impact score of this scenario is set to 100 %. The impact from the other two scenarios is then related to the one from Scenario 3 – Biogas. This result show that the reduction for the other two scenarios is almost as big as the one from Scenario 3 – Biogas, 94 % for Scenario 2 – Mussel meal and 95 % for Scenario 4 – Compost.
Figure 17. Comparison of the reduction of eutrophication of Scenario 2 – Mussel meal, Scenario 3 – Biogas and Scenario 4 – Compost in relation to each other. Scenario 3 – Biogas has the biggest reduction and is therefore set to -100 %. The reduction of Scenario 2 – Mussel meal and Scenario 4 – Compost is -94 % and -95 % of the reduction of Scenario 3 – Biogas respectively.

Within the climate change impact category, the difference between the scenarios is bigger than in the eutrophication impact category, however, all three scenarios have a contribution within the impact category, see Figure 18. Scenario 2 – Mussel meal has the highest contribution and is therefore set to 100 %. The impact from Scenario 3 – Biogas and Scenario 4 – Compost is then respectively 17% and 34% of the impact from Scenario 2 – Mussel meal.

Figure 18. Comparison of the contribution to climate change for Scenario 2 – Mussel meal, Scenario 3 – Biogas and Scenario 4 – Compost in relation to each other. Scenario 2 – Mussel meal has the highest impact and is therefore set to 100 %. The impact for Scenario 3 – Biogas and Scenario 4 – Compost is then respectively 17% and 34% of the impact for Scenario 2 – Mussel meal.

To see the reason for differences in the different scenarios and impact categories, the result will now be presented in real numbers and per life cycle stage.

As already established, all three scenarios have a net reduction of eutrophication and Figure 19 shows that this is mainly because of the nutrient reduction from the mussels, and somewhat because of the
avoided impact from “Avoided products”. All three scenarios have the same reduction from the mussels and contribution from the managing of the farm, hence it is the transport, production of the mussel products and avoided products that constitutes the differences in the net reduction. The reason that Scenario 2 – Mussel meal has the lowest reduction of eutrophication is mainly because of the transport of the mussels (yellow part of the stack) which is much longer compared to the transport in the other two scenarios. The mussels are transported by fossil fuelled trucks in all three scenarios, which releases the eutrophicating substances nitrogen oxides. The longer the transport, the more emissions are released and therefore this part of the life cycle is biggest in Scenario 2 – Mussel meal. In Scenario 2 – Mussel meal the energy used in the production (green part of the stack) also has eutrophicating impact which is due to the high electricity need. Since the production is in Norway, their electricity mix is used in the modelling which is mainly based on renewable energy and biofuels (wood chips) but also a small part of natural gas is used. Scenario 3 – Biogas barely has any eutrophicating impact from the transport or the production of biogas, which means that the result is fairly similar to the one in Scenario 1 – Mussel farm. In Scenario 4 – Compost, the main eutrophating impact comes from the ammonia released during the composting (dark red part of the stack). The material for the production (blue part of the stack) does not contribute significantly to eutrophication in any of the three scenarios.

For the climate change impact category, the results vary more, but Scenario 2 – Mussel meal, Scenario 3 – Biogas and Scenario 4 – Compost all have a contribution to climate change, see Figure 20. Scenario 2 – Mussel meal have the highest contribution and Scenario 3 – Biogas the lowest. The impact from the mussel farm is the same in all three scenarios and therefore the differences derives from transport, the production of the mussel products and the avoided impact from “Avoided products. The main
reason for Scenario 2 – Mussel meal contributing the most to climate change is due to the long transportation of the mussels (see yellow part of the stack). Since the trucks are assumed to be fossil fuelled in all scenarios they emit carbon dioxide which contributes to climate change. The longer the transport, the higher the emissions which is why the “transport” stack is the highest in Scenario 2 – Mussel meal. Another reason for Scenario 2 – Mussel meal having the highest impact in climate change compared to the other two scenarios is the energy and material used in the production of mussel meal. The electricity use in the production of mussel meal is rather high in comparison to the other two scenarios which is the main reason for that “Energy use production” (green part of the stacks) in Scenario 2 – Mussel meal is bigger than in the other two scenarios. Since the mussel meal production is assumed to be in Norway, Norwegian electricity mix is used in the modelling for this scenario, which mainly is based on renewable energy and biofuels (wood chips) but also a small part of natural gas is used. In Scenario 3 – Biogas, Swedish electricity mix is used (in Scenario 4 – Compost no electricity is needed for the production), which have a higher impact in climate change per kWh, however, the electricity use is much lower in Scenario 3 – Biogas and therefore the total impact from the electricity is less in Scenario 3 – Biogas compared to Scenario 2 – Mussel meal. In Scenario 3 – Biogas, part of the impact from “Energy use production” (green part of the stack) derives from the heat used in the production. The heat is assumed to come from waste incineration and therefore have emissions of carbon dioxide. The impact from “Material production” (blue part of the stack) in Scenario 2 – Mussel meal mainly derives from the production of sodium hydroxide which is rather energy extensive. In addition, almost 10 tonnes of sodium hydroxide are used in the production of mussel meal. In the other two scenarios no material is used (Scenario 3 – Biogas) or no impact in climate change derives from the material used (Scenario 4 – Compost). In Scenario 4 – Compost, part of the impact in climate change comes from the emissions of nitrous oxide from the composting (red part of the stack). In all three scenarios, “Avoided products” (dark blue part of the stacks) give a reduction in climate change, however, this reduction is small in comparison to the contribution within the impact category. Part of the reason why Scenario 3 – Biogas has the smallest impact in climate change is because “Avoided products” has the biggest reduction in this scenario compared to the other two scenarios. In this scenario, both fossil fuel and mineral fertilizer are assumed to be replaced by the biogas and biofertilizer produced from the mussels. Remember that only the production of the avoided products, not the use of them, is included in this analysis. How much mineral fertilizer that can be avoided depends on the plant available nutrient content in the biofertilizer or the compost. The plant available nutrient content in turn depends on the nutrient losses and other processes during the digestion or composting processes, which varies depending on the technique and substrate. Both refineries (production of fossil fuel) and extraction of nitrogen from the air (for the N-part of the mineral fertilizer) are energy extensive processes and stands for the main part of the avoided impact in Scenario 3 – Biogas. In Scenario 4 – Compost, mineral fertilizer is also avoided, however, the amount that can be avoided by the compost is much lower than the amount that biofertilizer can replace. Therefore, the avoided impact from the “Avoided products” in Scenario 4 – Compost is less than in Scenario 3 – Biogas. In Scenario 2 – Mussel meal and Scenario 4 – Compost, the shells are either directly included in the product (compost) or assumed to be a usable by-product (mussel meal). The shells consist of calcium which can replace limestone in different applications, for example in agriculture. Therefore, lime is included as an avoided product in those scenarios, however, the production of lime does not contribute significantly to climate change and thus is the avoided impact small. Although the shells are separated in the biogas scenario as well, they are assumed to be mixed with other “wastes” in the separation process and therefore not suitable for lime production. In Scenario 2 – Mussel meal fish meal, apart from lime, can be replaced. For the fishmeal, the main contributing process within the climate change impact category is the fishing of the fish.
Figure 20. The result within the climate change impact category show that all three scenarios have an impact and the differences mainly derives from transport. This result is for the reference flow (1 tonne mussels) and is presented with the unit kg CO\textsubscript{2}-equivalents. The light blue part of the stacks, “Mussels”, corresponds to the nutrient reduction from the mussels and is therefore not applicable in this impact category. The orange part of the stacks, “Material farm” corresponds to the impact from the production of the plastic, concrete and steel needed for the equipment for the farm. The grey part of the stacks, “Energy use farm” corresponds to the impact from combustion of fossil fuel in the boat. “Transport” corresponds to the yellow part of the stacks. The blue part of the stacks, “material production”, and the green part of the stacks, “Energy use production”, corresponds to the material and energy needed to produce the different mussel products. The dark blue part of the stacks, “Avoided products” stands for the avoided impact for not producing the replaced products. “Compost emissions” (red part of the stacks) includes the emissions from composting and is only applicable in Scenario 4 – Compost.

If the result is presented for 1 harvest (75,5 tonne mussels) instead of per tonne mussels, Figure 21 shows that there is a net reduction of eutrophication and the relation between the life cycle stages are the same as before. This is due to the linearly scaling from 1 tonne to 75,5 tonnes mussels.
Figure 21. This result shows the magnitude of the net reduction of eutrophication for each scenario when 1 harvest of the St. Anna farm which equals 75.5 tonnes mussels is studied. The is presented with the unit kg N-equivalents. The light blue part of the stacks, “mussels”, corresponds to the nutrient reduction from the mussels. The orange part of the stacks, “material farm” corresponds to the impact from the production of the plastic, concrete and steel needed for the equipment for the farm. The grey part of the stacks, “energy use farm” corresponds to the impact from combustion of fossil fuel in the boat. “Transport” corresponds to the yellow part of the stacks. The blue part of the stacks, “material production” and the green part of the stacks “energy use production” corresponds to the material and energy needed to produce the different mussel products. The dark blue part of the stacks, “avoided products” stands for the avoided impact for not producing the replaced products. “Compost emissions” (red part of the stacks) includes the emissions from composting and is only applicable in Scenario 4 – Compost. The net result shows a reduction of eutrophication in all three scenarios (the number above the stack).

Figure 22 show the magnitude of the impact to climate change for the three scenarios when studying one harvest (75.5 tonne mussels) instead of 1 tonne mussels. The relative contribution between the life cycle stages is the same as for the result for 1 tonne mussels but the magnitude is higher, which comes from the linearly scaling of the result.
Figure 22. The result shows the magnitude of the contribution to climate change for each scenario when 1 harvest, which equals to 75.5 tonne mussels, is studied. This result is presented with the unit tonne CO$_2$-equivalents. The light blue part of the stacks, “mussels”, corresponds to the nutrient reduction from the mussels and is therefore not applicable in this impact category. The orange part of the stacks, “material farm” corresponds to the impact from the production of the plastic, concrete and steel needed for the equipment for the farm. The grey part of the stacks, “energy use farm” corresponds to the impact from combustion of fossil fuel in the boat. “Transport” corresponds to the yellow part of the stacks. The blue part of the stacks, “material production”, and the green part of the stacks, “energy use production”, corresponds to the material and energy needed to produce the different mussel products. The dark blue part of the stacks, “avoided products” stands for the avoided impact for not producing the replaced products. “Compost emissions” (red part of the stacks) includes the emissions from composting and is only applicable in Scenario 4 – Compost. The net result shows a contribution to climate change in all three scenarios (the number above the stack).

9.2.1 Sensitivity analysis – Transport variation

The transport variation analyses different possibilities of production sites for each scenario and two types of fuel for each site. A recap on what each variation includes are given in Table 13. The number in the name refers to which scenario the variation is based on and the letter in the name refers to the different variations.
Table 13. A recap of the different transport variations of Scenario 2 – Mussel meal, Scenario 3 – Biogas and Scenario 4 – Compost. The name, location of the production site, distance and fuel is presented. For a detailed description of the inputs, see Table 10 - Table 12.

<table>
<thead>
<tr>
<th>Name on variation</th>
<th>Location production site</th>
<th>Distance (km)</th>
<th>Way of transportation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 2</td>
<td>Tromsö, Norway</td>
<td>1 764</td>
<td>Fossil fuelled truck</td>
</tr>
<tr>
<td>Scenario 2a</td>
<td>Tromsö, Norway</td>
<td>1 764</td>
<td>Non-fossil fuelled truck</td>
</tr>
<tr>
<td>Scenario 2b</td>
<td>Limfjorden, Denmark</td>
<td>900</td>
<td>Fossil fuelled truck</td>
</tr>
<tr>
<td>Scenario 2c</td>
<td>Limfjorden, Denmark</td>
<td>900</td>
<td>Non-fossil fuelled truck</td>
</tr>
<tr>
<td>Scenario 2d</td>
<td>St. Petersburg, Russia via Västervik</td>
<td>958</td>
<td>Fossil fuelled truck + heavy fuel oil cargo ship</td>
</tr>
<tr>
<td>Scenario 2e</td>
<td>St. Petersburg, Russia via Västervik</td>
<td>958</td>
<td>Non-fossil fuelled truck + natural gas cargo ship</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>Linköping, Sweden</td>
<td>77,8</td>
<td>Fossil fuelled truck</td>
</tr>
<tr>
<td>Scenario 3a</td>
<td>Linköping, Sweden</td>
<td>77,8</td>
<td>Non-fossil fuelled truck</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>Högbytorp (Stockholm), Sweden</td>
<td>247</td>
<td>Fossil fuelled truck</td>
</tr>
<tr>
<td>Scenario 4a</td>
<td>Högbytorp (Stockholm), Sweden</td>
<td>247</td>
<td>Non-fossil fuelled truck</td>
</tr>
<tr>
<td>Scenario 4b</td>
<td>Kil (Karlstad), Sweden</td>
<td>288</td>
<td>Fossil fuelled truck</td>
</tr>
<tr>
<td>Scenario 4c</td>
<td>Kil (Karlstad), Sweden</td>
<td>288</td>
<td>Non-fossil fuelled truck</td>
</tr>
<tr>
<td>Scenario 4d</td>
<td>Zero transportation</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>

The result from the sensitivity analysis in the eutrophication impact category shows small variations between the different sites and a slightly bigger variation between the two types of fuel for the same site, see Figure 23. The result is presented for the entire life cycle, however, it is only the yellow part of the stack (“Transport”) that is varied in respect to the reference scenarios. The reason for the small differences regarding the transportation distance is the assumed high standard on the emissions control of the trucks (EURO6) which leads to relatively low emissions of nitrogen oxides. The difference between a fossil-based fuel and a vegetable oil-based fuel, biodiesel on the same transportation distance is, on the other hand, relatively big. For example, the contribution to eutrophication is around four times higher for Scenario 2a (non-fossil fuel) compared to Scenario 2 (fossil fuel) even though the transportation distance is the same. The reason for this is found in the composition of the biodiesel. The biodiesel assumed to be used in this study is mainly based on rapeseed and during the cultivation of the rapeseed nutrients is leaked which cause eutrophication. However, the result shows that regardless of production location site and type of fuel, the system has a net reduction within the eutrophication impact category.
Figure 23. The result from the sensitivity analysis on transportation variation within the eutrophication impact category show small variations between the different sites and slightly bigger variation between the different types of fuel for the same site. The result is based on 1 tonne mussels and presented with the unit kg N-equivalents. Scenario 2 – Mussel meal, Scenario 3 – Biogas and Scenario 4 – Compost are reference scenarios and a-e are variations of those. For Scenario 2 – Mussel meal and Scenario 4 – Compost the variations include different locations of the production site and two types of fuel for each site. For Scenario 3 – Biogas, only one production site is analyzed, and the variation therefore only include two types of fuel for the same site. For visualization of the net impact for the different variations, the result for the entire life cycle is presented however, it is only “Transport” (yellow part of the stack) that is varied. This part is marked with black contour for easier recognition.

For the climate change impact category, the result from the sensitivity analysis varies more where shorter distance and non-fossil fuel shows a better result, see Figure 24. The result is presented for the entire life cycle, however, it is only the yellow part of the stack (“Transport”) that is varied in respect to the reference scenarios. For the fossil fuelled variations, it is the carbon dioxide emissions released during the combustion of the fuel in the engine that is the main reason for the climate change impact, and those increase linearly with the distance. Carbon dioxide is also emitted from the combustion of the biodiesel, however, the same carbon dioxide is used by the rapeseed for its photosynthesis. The means that the net carbon dioxide emitted in regard to the combustion, is zero. The impact on climate change for biodiesel is therefore much lower compared to fossil fuel, and the small impact comes from the production of the fuel. For example energy and material needed for the culturing the rapeseed and the extraction of the oil.

There is one exception in the result; Scenario 2d and 2e. The distance in those scenarios (2d and 2e) is slightly longer than the distance in Scenario 2b and 2c, however, the impact from the transport in Scenario 2b is around five times higher than in 2d (both fossil fuel) and the impact from 2c (fossil fuel) is around three times higher than in 2e (non-fossil and natural gas). Furthermore, the impact from transport in 2d, fossil fuel, is lower than in 2c, non-fossil, even though the distance in 2d is longer. This is due to the different ways of transportation; only truck versus mainly cargo ship. A truck cannot transport as much weight or volume at the same time as a cargo ship. Since the total emissions from the truck or cargo ship are allocated to the transported goods by mass or volume, each unit of weight...
or volume only accounts for a part of the total emissions. Even though the total emissions from a cargo ship probably are higher than the ones from a truck, the emissions allocated to the mussels are smaller when transported by cargo ship. The change of fuel for the cargo ship is from heavy fuel oil to natural gas, both are fossil-based and thus have carbon dioxide emissions from the combustion. Therefore, the difference between Scenario 2d and 2e is smaller than for all other variations of the same distance but different fuel (for example comparing Scenario 2 and 2a). The result shows that regardless of fuel, Scenario 3 has the lowest impact in climate change compared to all other variations. Within Scenario 2 it is the 2e variation (St. Petersburg, non-fossil fuelled truck + natural gas cargo ship) that has the lowest impact in climate change, however, 2d (St. Petersburg, fossil fuel) also has lower impact than all other variations of Scenario 2. Within Scenario 4 it is the 4d variation (Zero transportation) that has the lowest impact in climate change.

![Climate change, kg CO\(_2\)-eq. 1 tonne mussels](image)

9.3 Normalization

Normalization is done on all four scenarios on the result based on 1 harvest of the St. Anna farm (75,5 tonnes mussels). The normalized result relates the impact from the life cycle of the mussels with a reference scenario and aims at simplifying the understanding of the environmental performance of the analyzed system. In this case, the reference scenario is chosen to be the impact from an average European. Since the life cycle of the mussels is assumed to be two years, the reference scenario is the impact from an average European during two years. The reference scenario is set to one and the result from the three scenarios is then expressed as “how many average European it corresponds to”.
In the normalized result within the eutrophication impact category, shown in Figure 25 it can be seen that all four scenarios reduce eutrophication corresponding to the impact of more than 20 average Europeans. Scenario 3 – Biogas has a lower normalized score than Scenario 1 – Mussel farm, which means that Scenario 3 – Biogas reduces eutrophication more than only the mussel farm itself. When comparing Figure 13 and Figure 21 the same is seen as for the non-normalized result. From the same comparison, it can also be seen that the reason for this is the further reduction “Avoided product” has in combination with only a slight increase in eutrophating emissions from “Transport” and “Energy use production”. This result show that a bigger reduction of eutrophication is achieved if the mussels are used to produce biogas and biofertilizer than if nothing is done with the harvested mussels. However, all four scenarios have fairly similar impact score which implies that the reduction of eutrophication is not significantly affected when the harvested mussels are valorized into a mussel product.

![Eutrophication Chart](image)

*Figure 25. The normalized result in the eutrophication impact category show that all four scenarios reduces eutrophication corresponding to more than the impact from 20 average Europeans. Scenario 3 – Biogas has the biggest reduction, even when for only the mussel farm itself is studied (Scenario 1 – Mussel farm) The result is based on 1 harvest of the St. Anna farm (75,5 tonnes mussels) and normalized against a reference scenario which corresponds to the eutrophating emissions from an average European released during two years. To calculate the normalized result the total impact within this impact category in each scenario is divided with the reference scenario. The normalized result is presented as “how many times the reference scenario fits within the impact from each scenario”.*

The normalized result for the climate change impact category shows that Scenario 1 – Mussel farm and Scenario 3 – Biogas have lower impact than an average European whereas Scenario 2 – Mussel meal and Scenario 4 – Compost have higher impact than an average European, see Figure 26. Scenario 3 – Biogas has lower impact than Scenario 1 – Mussel farm which is confirmed by comparing Figure 14 and Figure 22. The reason for this is that “Avoided products” in Scenario 3 – Biogas reduces the impact more than what “Transport” and “Energy use production” in the same scenario contributes to climate change. This result shows that if the mussels are valorized into biogas and biofertilizer (Scenario 3 – Biogas), the impact on climate change is reduced compared to if nothing is done with the harvested mussels (Scenario 1 – Mussel farm). The result also shows that if the mussels are valorized into mussel meal (Scenario 2 – Mussel meal) the contribution to climate change increases around four times compared to if nothing is done with the harvested mussels (Scenario 1 – Mussel farm). For Scenario 4 – Compost, there is a slight increase in the impact compared to Scenario 1 – Mussel farm.
Figure 26. The normalized result within the climate change impact category show that Scenario 2 – Mussel meal and Scenario 4 – Compost contribute to climate change more than one average European whereas Scenario 1 – Mussel farm and Scenario 3 – Biogas contribute less than one average European. Scenario 3 – Biogas has the lowest contribution to climate change even compared to only the mussel farm itself (Scenario 1 – Mussel farm). The result is based on 1 harvest of the St. Anna farm (75.5 tonnes mussels) and normalized against a reference scenario which corresponds to the climate change contributing emissions from an average European released during two years. To calculate the normalized result the total impact within this impact category from each scenario is divided with the reference scenario. The normalized result is presented as “how many times the reference scenario fits within the impact from each scenario”.

![Graph showing normalized climate change impact](image-url)
10 Discussion

In this chapter mussel farming as an environmental measure is discussed based on the result from the LCA and compared to other similar studies. Furthermore, possible improvements to the system is discussed as well as environmental effects which are not included in the LCA. Lastly, the chosen method (LCA) and modelling principles are discussed.

10.1 Mussel farming as a tool for mitigating eutrophication

As confirmed in the result from Scenario 1 – Mussel farm, the nutrient uptake from the mussels is greater than the contribution from managing the farm and thus the mussel farm has a net reduction of eutrophication. Although the result is presented with another unit, the same was shown by Spångberg, Jönsson and Tidåker (2013) and Aubin et al. (2017). When including transportation and the production of the different mussel products, the result for research question 2 show that there is not a significant change in the net reduction of eutrophication for the studied system. Production of biogas is the most beneficial one from this perspective and from the normalized result it is shown that if production of biogas is done, the net reduction of eutrophication is greater than for only the mussel farm. This is due to the inclusion of “Avoided products” in the analysis, which for Scenario 3 – Biogas mean avoided production of fossil fuel and mineral fertilizer. The avoided impact from the avoided production in this scenario is greater than the increased impact from production of biogas and biofertilizer in the same impact category. The net result, when also including the mussel farm, still show a contribution to climate change, however, it is smaller than for the farm itself (Scenario 1 – Mussel farm). The inclusion of “Avoided products” is a way of modelling called system expansion, which is the way preferred in the ISO standard (European Commission, 2010). When studying emerging technology and new products as well as systems with multiple functions, this way of modelling is especially useful according to Hospido et al., (2010) and Spångberg, Jönsson and Tidåker (2013). However, using system expansion creates a complex system which is time consuming and therefore the expansion cannot be done all the way in most cases and thus allocation needs to be used instead. In this study, system expansion is partially done since only the production of the avoided products are included and not the use of them. If the use of the avoided products was to be included, the result would be different. For example, if combustion of the fossil fuel was to be included, for Scenario 3 – Biogas, the avoided impact would be higher in both impact categories. This is because the emissions of nitrogen oxides and carbon dioxide are significant when combusting fossil fuels, substances that respectively contribute to eutrophication and climate change.

The nutrient reduction from mussel farms is dependent on the amount of mussels in the farm and the size of the mussels. This is in turn dependent on the conditions of the location where the farm is placed. Conditions that affect the growth of the mussels are for instance the salinity, strength of the current and the presence of predators. This study shows that a farm with a size of 0,5 ha can give a harvest of 75,5 tonne mussels which give a reduction of 830 kg nitrogen and 83 kg phosphorus over two-year period. A similar study indicates a slightly smaller nutrient reduction of 600 kg nitrogen and 40 kg phosphorus from mussels farmed in the Baltic Sea on the same area and time frame (Spångberg, Jönsson and Tidåker, 2013). No investigation on the total area along the Swedish east coastline which fits these conditions has been made (Gren, Lindahl and Lindqvist, 2009). However, one study estimates that there are 500 ha suitable for mussel farming in the archipelago of Östergötland (Nordell, 2010) and another study estimates that there are 800 ha suitable for mussel farming along the coast between northern Stockholm and Karlskrona (Gren, Lindahl and Lindqvist, 2009). This means that the nutrient reduction from mussel farms is limited and thus cannot fulfill the objective of “good environmental status” in the Baltic Sea alone. However, it can be a good complement to the already existing nutrient reduction methods such as waste water treatment plants.
and wetlands. Partly because those measures also have limitations, the purification level in Sweden in general is 95% for phosphorous and 60-70% for nitrogen (Naturvårdsverket, 2016). But mainly because mussel farming reduces the nutrients already in the sea, which makes it a good measure for reducing the internal load of nutrients, something that land-based actions cannot achieve. As mentioned before, “good environmental status” will take much longer time to reach if those internal loads are not removed even though the nutrient input to the Baltic Sea would cease. On the west coast of Sweden, the success of mussel farming and waste water treatment working together is already demonstrated. In Lysekil, a mussel farmer harvested 3,500 tonnes mussels each year as a nutrient reduction method which lead to a 100% nitrogen removal from the municipal waste water together with the existing waste water treatment plant (Lindahl and Lovén, 2008). Something worth remembering is that the mussels grow faster and become bigger on the west coast due to the higher salinity, which means that the harvest per hectare is bigger and therefore also the nutrient removal. However, farming mussels in the Baltic Sea also works to mitigate the eutrophication, as the result from this study show, but the potential of the removal is lower per hectare compared to the west coast and the mussels need an extra period to be harvested.

A quick arithmetic example indicates the potential of reduction of phosphorus if the assumed 800 ha suitable for mussel farming are used and the conditions for the farms are the same as for the St. Anna farm. This would give a removal of 133 tonnes of phosphorus over a two-year period. In 2016, Naturvårdsverket estimated that the implemented and planned actions for phosphorous reduction until 2021 would leave 130 tonnes to be removed in order to reach the goals for Sweden in the BSAP (Ejhed et al., 2016). This example show that the mussel farms have potential to help Sweden fulfill the goal of reduction of phosphorus within the BSAP, similar to what many studies have concluded before (Gren, Lindahl and Lindqvist, 2009; Lindahl, 2012; Petersen et al., 2014). Note that the goal of “good environmental status” is not automatically reached even though the goals of nutrient reduction are reached. Furthermore, this arithmetic example does not consider the emissions of phosphorous from the managing of the farm. However, as the result from Scenario 1 – Mussel farm show, the managing of the farm does not majorly affect the net nutrient reduction of the system and thus should not majorly affect the phosphorous reduction either.

However, from the result it is clear that the reduction in eutrophication from this system comes at a cost in contribution to climate change. Most actions for one environmental problem comes at a cost for one or more other areas and the challenge is to reduce the cost as much as possible. This is where the method LCA evolves from. Since several impact categories are included in this type of analysis, sub optimization is minimized and the measure with the lowest environmental cost can be identified as well as possible solutions to reduce the environmental cost. This is also applicable within strategies for reduction of nutrients and thus mitigation of eutrophication. Waste water treatment plants, wetlands and mussel farming all help mitigate eutrophication at a cost of climate change among other things. A study by Åmand et al., (2016) investigates the effects on the total environmental performance of waste water treatment plants (WWTP) when increasing the level of purification. The study concludes that the effects differ between different treatment plants depending on the present technology and the necessary changes to achieve the specific level of purification. Regardless, all waste water treatment plants reduce eutrophication but contribute to climate change among other things (Åmand et al., 2016). We can, from the normalized result, see that the reduction of eutrophication is bigger than the contribution to climate change for the mussel farm. However, this does still not tell us which if the impact categories that is the most dangerous or most important one, in the same way, it does not give an answer to whether it is a good or bad environmental measure. Locally, in the Baltic Sea, eutrophication is a critical environmental problem and globally climate change is a critical environmental problem. Which of the two impact categories that are the most
important is normally determined in the weighing step which is not included in this LCA. This step is subjective and depends on many specific factors, such as the sensitivity of the receiving environment, national or international politics or even the interest of the decision maker (European Commission, 2010). In summary, to decide whether farming mussels is a positive or negative measure for reduction of eutrophication it needs to be compared to other, similar measures and their climate change contribution in relevance to their nutrient reduction, something that is not covered in this study. The actual cost, as in monetary measures, is also of interest when analysing the performance of a nutrient reduction strategy but is also not covered in this study.

10.2 Development of the system

The result show that the activities concerning the management of the farm, transportation and the production of the different mussel products all have impact on both impact categories. The overall environmental performance of the farm is dependent on the impact from those stages in combination with the mussels’ potential of nutrient removal. Thus, any improvements or changes to the system can have an impact on the result and the overall environmental performance, as the sensitivity analyses show. The energy used in the farm consists of petrol combusted in a boat either for transportation of the boat or hydraulic to run the harvest equipment. Boat engines do not have the same restrictions on exhaust emissions control as road vehicles and therefore emits more eutrophating emissions such as nitrogen oxides (Naturvårdsverket, 2009). Furthermore, technology development has not come as far on boat engines which results in the technique for exhaust emission control being way behind compared to engines road vehicles. To reduce emissions and the impact in eutrophication and climate change from the energy used in the mussel farm the fuel should be changed from fossil fuel to a more environmental fuel or green electricity. In addition, the fuel should be used more conservatively. From the sensitivity analysis on Scenario 1 – Mussel farm we can see that an upscaling of the farm makes it more energy efficient per tonne mussel and thus the impact from this stage in the life cycle is reduced. Further improvements to the farm, other than the ones analysed in the sensitivity analysis could include a more energy efficient boat which would reduce the emissions and thus the environmental impact further. There also exists other alternatives of more environmental fuel than electricity as well as other electricity mixes than the Swedish mix, which could affect the result.

When it comes to the material, the sensitivity analysis show that the size of the farm does not have a significant impact on the material use. All materials used in the farm are assumed to be virgin material, hence it is not recycled or reused. Moreover, it is assumed to last for ten years which corresponds to five life cycles of the mussels. The life length is based on an assumption from the mussel farmer Mats Emilsson (2018) that the fuzzy ropes the mussels grow on can last for ten years which equals to five harvests, and the same life length is then used for the rest of the material. The steel and the concrete probably could last longer than ten years which would result in a lower impact per tonne mussels. On the other hand, if the material does not last as long as predicted, the impact per tonne mussels would instead increase. To reduce the impact of the material, recycled material, instead of virgin could be used. Another solution could be to try to replace it with more environmentally friendly material, for example, use a non-fossil-based material instead of plastic. When it comes to the plastic used in the farm there is also another issue than the impact on climate change, something that is not analyzed in the LCA. That is the emissions of microplastics and contribution to marine litter, more about this in section 10.3. Since the requirements on the material is rather high; it is constantly fully submerged in salt water, during winter it will be covered by ice and the mussels should easily be able to grow on it, a thorough investigation on a possible substitution need to be done. To the authors knowledge, no other farm has tried other material than plastics. However, the farming technique can influence the
amount of material and energy needed per tonne mussels, which of course influences the result. Spångberg, Jönsson and Tidåker (2013) have done a life cycle assessment on a farm in Kalmar which uses another technique than the long-line used in the St. Anna farm, but with the same primary function; an environmental measure. In their analysis the contribution to climate change per tonne mussels is almost half of the contribution the result in this study shows. When analysing this, we saw that both the material and the energy needed for the farm was substantially lower per tonne mussels in their study compared to this study. Irribarren (2010) have done an LCA on yet another farming technique which is used on a farm in Spain where the mussels are farmed for human consumption. His result shows a contribution to climate change almost 4 times higher per tonne mussels compared to the St. Anna farm. The big difference can be explained by both a different farming technique and conditions for the farm, but also differences in the modelling since Irribarren (2010) includes capital goods in the analysis. Yet another LCA with a different farming technique for mussels for human consumption situated in the English Channel present a much lower contribution to climate change per tonne mussels, almost zero (Aubin et al., 2017). This is because they include a reduction of carbon dioxide by both the mussels and the wood used in the farm. If this reduction is not included, the same study presents a contribution to climate change almost 50 % higher per tonne mussels compared to this study. This shows that the farming technique, but also the modelling of the system, can have a significant impact on the environmental performance for the farm. What can also be seen is that mussels farmed for human consumption generally have higher impact on climate change compared to mussels farmed as an environmental measure. This is probably because the quality requirements, especially aesthetics, is lower for mussels farmed as an environmental measure which result in bigger harvest per square meter farm. Petersen et al. (2014) have come to the same conclusion regarding the economic cost for a mussel farm; a mussel farm optimized for nutrient removal can have a lower cost compared to production for human consumption. Within the eutrophication impact category on the other hand, a comparison of the studies mentioned, including this one, show that the farming technique does not significantly impact the result. The big difference in this impact category is whether the nutrient removal from the mussels are included or not. If the nutrient removal is included, there is always a net reduction of eutrophication. The studies which do not include the nutrient removal include mussel farms with the primary function to produce human food and thus have less focus on the marine eutrophication impact category.

Transport is one of the main contributing processes to both eutrophication and climate change. In this LCA, the transport is assumed to be by trucks in the European emission standard EURO6 class which means that they have the best available technique for vehicle emissions control (Williams and Minjares, 2016). One of the focuses in the European emissions standard, where EURO6 is the strictest class, is reducing emissions of nitrogen oxides (Williams and Minjares, 2016), compounds that among other things contribute to eutrophication. The technological development could reduce these emissions further in the future but with available technology today (year 2018) the only ways to reduce eutrophating emissions from transport by truck is either to reduce the distance or change fuel. Since no emission control of carbon dioxide exists in road vehicles today, the strategies to reduce these emissions will be the same; reducing the transport distance or change of fuel. The result from the sensitivity analysis on transport variation also tells us that, for the same distance, the impact on climate change is reduced if the fuel is changed from fossil fuel to non-fossil fuel, in this case vegetable oil-based biodiesel. Although, in the eutrophication impact category the biofuel has higher emissions than the fossil fuel when comparing the same transportation distance. This increased impact does however not affect the net reduction of eutrophication majorly. In the sensitivity analysis in this LCA only one fossil free fuel is included, and different fuels can affect the result in other ways. For example, we saw that a change from fossil fuel to electricity for the boat reduced the impact on climate change
without a visible increase of the impact in eutrophication. The result from the sensitivity analysis also tells us that a change of way of transportation also can be an efficient way of reducing the impact from transportation in both eutrophication and climate change. In this case the change is from truck to cargo ship. A cargo ship is said to be a more energy efficient way of transporting compared to a truck since each ship can take a larger load (Trafikverket, 2018). To reduce emissions from transport, a change from truck to cargo ship or possibly even train could be an alternative. A part of the national and international strategy to reduce environmental impact from the transport sector is to reduce the transport by truck and increase the transport by cargo ship and trains (Trafikverket, 2018). Therefore, the 2d and 2e variation of Scenario 2 – Mussel meal could be seen as the most promising from an environmental perspective in this scenario and are also in line with the future strategies for the transport sector. Although not covered in this study, there are possibilities to replace the transport by truck even in the other two scenarios. The mussels could be shipped parts of the way in variation 2b and 2c and sent by train in the reference variation Scenario 2 and 2a, which probably would reduce the environmental impact. Still, the transport variations in Scenario 2 – Mussel meal and Scenario 4 – Compost with the lowest impact in eutrophication from “Transport” has a lower net reduction of eutrophication than all variations in Scenario 3 – Biogas. The same can be seen within the climate change impact category.

To reduce the impact from those stages directly connected to the production of the different mussel products the energy and material could be used more efficiently or be changed to more environmental friendly alternatives, and the compost emissions could be reduced. For Scenario 2 – Mussel meal, the numbers used for the material and energy needed in the production is based on an actual production of a trial batch of mussel meal. However, since the production was a trial it was not optimized for mussel meal which probably resulted in a higher consummation of energy and material than in a commercialized production. Furthermore, today’s technology for producing mussel meal is not that developed and even though mussel meal is produced in small scale by some industries, the production of it is far from optimized. However, with more and more testing and learning, the process and industry of mussel meal have potential to become better. Increased uncertainties around inputs and outputs for processes is something that Hetherington et al. (2014) reports as common for new and developing products. However, Hetherington et al. (2014) also mentions the value of an LCA in an early research stage in order to highlight and target improvement areas and drive the development towards increased sustainability. Possible improvements that we see concern both the exchange ratio of mussel meal from mussels and the overall energy efficiency of the production. Compared to the production of fish meal, which is the product aimed to be replaced by mussel meal, the production of the mussel meal is very inefficient. For mussel meal to be able to compete with the existing fish meal production and market, the production must become more efficient (Tasse pers. com., 2018). This could result in less environmental impact as well. In the modeling of Scenario 2 – Mussel meal an exchange ratio between mussels and mussel meal of 32,7 is used and another facility in Sweden that has a small scale production of mussel meal reports a ratio of 20 (Kollberg and Lindahl, 2004). This shows that there is potential of decreasing the ratio. Note that an improve exchange ratio would not affect the impact from either “Material production” or “Energy use production” per tonne mussel since only more mussel meal per tonne mussel would be produced. This would, however, slightly affect the net result since “Avoided products” would change because more fish meal can be avoided if more mussel meal is produced. In Scenario 4 – Compost, the overall environmental performance for this scenario would improve with reduced compost emissions. The amount of emissions released during the composting depends on the material but mostly on the way it is composted. The emissions from this stage could, therefore, be reduced by improving the way of composting, hence reducing the climate change impact.
10.3 Effects of the system not included in the LCA

Mussels produce feces when they eat, like all other animals. The feces contain nutrient and sinks to the bottom when they are released from the mussels. Therefore, the organic matter under the farm is increased and since it needs to be decomposed, oxygen is consumed which can lead to or increase already existing hypoxic bottoms. The extra organic matter under the farm can also include dead mussels that have fallen off the ropes and down to the bottom. Since no mussel spat is added to the sea when farming mussels, a farm only provides a place for the mussels to grow on, the process is natural and present even without the mussel farm. However, a farm concentrates the mussels which in turn concentrates the feces to a more limited area. From hypoxic bottoms, nutrients such as nitrogen and phosphorous are released from the sediment. Nitrogen is mostly released as ammonium which has a higher eutrophication effect than other nitrogen compounds, such as nitrogen gas (Stadmark and Conley, 2011). Phosphorus is chemically bonded with oxygen in regular sediments and when the bottom becomes hypoxic the phosphorus is released, which also contributes to eutrophication. The amount of nutrients that are released from the sediment is dependent on how much oxygen that is available at the bottom. The oxygen levels in the sediment are in turn dependent on what type of sediment it is, the strength of the current and how big benthic fauna (Stadmark and Conley, 2011). So, if the location is chosen with aspect to these parameters, the increased organic matter falling to be bottom does not have to be a problem. Meaning that if the bottom doesn’t suffer from hypoxia and if it is slightly current, it would be a suitable location for mussel farming. Another way to prevent possibilities of increased hypoxia is to somehow collect the feces. Since the feces contain nutrients it could be a good possible fertilizer for farmlands, reducing the need for mineral fertilizer. This would also contribute to reducing the eutrophication since a circular flow of the nutrients is created. The same goes when using the mussels to produce biogas or compost. A circular flow of nutrients is created, and the use of mineral fertilizer is reduced. The usage of mineral fertilizer contributes to eutrophication when the nutrients leak from farmlands and may eventually end up in the sea since those nutrients are industrially produced and therefore adds to the nutrients already in flow. The leakage from organic fertilizer, such as digestate or compost, is in the same magnitude as for mineral fertilizer. However, since the nutrients have already been removed from the sea and therefore exists in the natural circular flow, the runoff from organic fertilizer does not contribute to the net inflow. The nutrients are removed from a place where they do damage to a place where they are needed, which means that the natural processes are not disturbed, and the planetary boundaries are not further crossed.

The food that the mussels eat when filtrating the water is phytoplankton (Jönsson, 2009; Lindahl, 2012). Extensive growth of phytoplankton, which happens when there is an abundance of nutrients, will decrease the transparency in the water (HELCOM, 2009). When the transparency decreases, it means that the sunlight doesn’t reach as deep in the water. With the sun not reaching down as far it makes it harder for plants to grow in the deep water. The decrease in plant growth means less production of oxygen which leads to less life in the water and that in time leads to hypoxic bottoms. Positive effects on the visibility in the water around mussel farms have been noticed (Petersen et al., 2014). This means that mussels not only mitigate eutrophication by removing nutrients from the water but by reducing the amount of phytoplankton and increasing the visibility as well.

Fish can count as a renewable source, but for the oceans to produce fish at a high rate and contain the ecosystem it must be handled in a reasonable and sustainable way (Engvall, 2012). In 2014 93,4 million tonnes of fish were captured and 73,8 million tonnes of aquatic animals were produced in aquaculture (FAO, 2016). Since the feed for farmed fish consists of fish meal and fish oil, it is said that 1,5-4 kilo captured fish is needed to produce 1 kilo of farmed fish, fish farms also highly contribute to
overfishing (Bruno, Garpe, and Holmquist, 2011). The mussels don’t need any extra food like farmed fish, it only needs something to grow on. Since mussel meal can replace fish meal it could contribute to the reduction of overfishing because the fish used for the production of fish meal doesn’t have to be captured.

As mentioned in chapter 3 the planetary boundary “interference with the nitrogen and phosphorus cycles” is crossed, which means that we have disrupted the natural cycles of these nutrients. Since the mussels remove the nutrients from the sea and is brought back to land a cycle of the nutrients is created and helps reduce the impact on the planetary boundaries. This mostly concerns Scenario 3 – Biogas and Scenario 4 – Compost because the biofertilizer from biogas production and the compost returns the nutrients directly. Looking outside the system boundaries, the nutrients can even be recycled in Scenario 2 – Mussel meal if the feces from the animals is used as fertilizer, which is common today. In the future this can be even more important with the growing population and the need for more nutrients in the agriculture and food production industry. The mussels also contribute to a stronger national food chain, which can be an important factor in the future as well. With a stronger national food chain Sweden would become less dependent on other countries for food supply, where this supply can be compromised in the future from e.g. political aspects.

There has been one study on the Baltic clam, Limecola balthica, which showed that the Baltic clam releases methane gas (Bonaglia et al., 2017). Methane gas has a global warming potential of 25 which means that it highly contributes to climate change. The Baltic clam lives in the sediment, unlike the blue mussels who always grows on hard surfaces (Bonaglia et al., 2017; Warén, 2018). Their conclusion is that this should apply to all mussels, and that this should be taken into account when mussels, mostly blue mussels, are farmed. There is a possibility that the blue mussels can release methane during their life cycle, but we think that since the study is not done on blue mussels specifically it is hard to tell. A more important factor to consider with this result is the fact that when blue mussels are farmed, the mussels are not added in the water, only the fuzzy ropes and other material is added to the water. This means that even if the mussels weren’t farmed, they would still be living and growing in the sea and, if the produce methane, release methane to the air.

Plastic and microplastic in the seas are major problems that only quite recently have been beheld. Microplastics are small particles of plastic, less than 5 mm. It has recently been identified as an environmental problem, mostly due to the high amounts of plastic litter that is found in the seas together with the low degradation rate of plastics (Lusher, Hollman, and Mendoza-Hill, 2017; Naturvårdsverket, 2017). It is not known to which extent if any, the plastics used for mussel farming contributes to microplastics (Lusher, Hollman, and Mendoza-Hill, 2017). However, since the lines are constantly in the water during their whole lifespan it is not impossible that they are exposed to some degradation during this time. Degradation of plastic is one of the biggest sources to microplastic (Naturvårdsverket, 2017). According to (Lusher, Hollman and Mendoza-Hill, 2017) abandoned, lost or otherwise disposed plastics from fishery is the sectors main contribution to the marine litter. There is no guarantee that no plastic will be lost from the farm and by that become marine litter, but it is important to prevent it if possible. The consequences on the marine life from plastics and microplastics are not entirely certain. However, scientists believe that the animals consume it, and since they cannot degrade the plastic it accumulates in their body resulting in starvation or suffocation (Naturvårdsverket, 2017). Bigger pieces of plastics, for example, lines and ropes, can also get stuck on the animal and hinder its natural development or swimming among other things. Although the mussel farm is supposed to be an environmental measure focusing on mitigating eutrophication, it is preferably done in a way which minimizes the contribution to other environmental issues. Therefore, it would be of interest to determine whether the plastic used contributes to microplastics and if so,
try to find an alternative. With a change in material, the contribution to climate change could also reduce.

### 10.4 Method

In this study, the choice fell on the life cycle assessment methodology to answer the research questions and fulfill the objective. Life cycle assessment is a method for quantifying the environmental impact of a product’s or service’s whole life cycle (Baumann and Tillman, 2004; European Commission, 2010). The result from an LCA gives indications of the environmental performance of a specific product or service. The method has, therefore, become more frequently used in the aquaculture sector in the process of better understanding the environmental impacts (Henriksson et al., 2012). The methodological choice for this study is supported by LCAs proved ability to provide the aquaculture industry with transparency and accountability within the sustainability area (Iribarren, Maria Teresa Moreira and Feijoo, 2010). There is a general framework to the LCA methodology along with general databases, computer programs, and other tools which simplifies the execution of an LCA. However, many decisions including system function, system boundaries and method for the impact assessment, lay within the executor’s hands. These decisions define the LCA and influence the result which is why it is important to understand those in order to fully understand the result. With this said, the results from an LCA can give indications to a product’s or service’s environmental performance in a specific context. One should, therefore, take caution in comparing results from different LCAs since the contexts of which the analysis is based on differ and thus the result. However, the four scenarios analyzed in this LCA are based on the same context and therefore it is possible to draw conclusions when comparing the results.

The characterization factors in most existing impact assessment methods are calculated to reflect the potential damage from the specific substance on an average or standardized “unit environment” (Hauschild, 2006). The impact of a specific substance in a specific impact category depends on complicated natural processes and the sensitivity of the receiving environment (Henryson, Hansson and Sundberg, 2018). Since LCA is a site generic tool, the characterization factors have historically always been global, and regional differences is not accounted for (Hauschild, 2006). This means that the result from an LCA could be different to the actual impact for a specific area. This is most evident in impact categories that have local or regional effect instead of global effect and the level of uncertainty is somewhat reduced when regional characterization factors are used (Hauschild, 2006).

Since this study has a geographical boundary limited to the Baltic Sea, which firstly is rather different to most other seas in the world and secondary is located in Europe, the decision was made to make a regionalised assessment. The chosen method, ILCD, uses characterization factors adapted to the average European environment in the necessary impact categories (European Comission, 2011). This makes it a regionalised method even though the region it is adapted to is rather big and contains different types of environments. Because of the latter, the level of uncertainty of the actual impact is still existing although probably less compared to if a generic method were used. Another parameter that inflicts uncertainty in the final impact is the amount of emissions ending up in a specific area. Studies on a limited geographical area, such as this study, are especially exposed to this kind of uncertainty as well as impact categories with local or regional effect. Diffuse emissions can travel far and the amount that affects a specific area instead of somewhere else is hard to predict. Eutrophication is an example on an impact category that has local or regional effect (Hauschild, 2006) and airborne nitrogen oxides from combustion of fossil fuel an example of a diffuse emission. Airborne NOx will dissolve in the water vapour in the air and eventually fall down together with the rain (Hansson and Elding, 2018). As the rain can practically fall anywhere, the amount of NOx emitted from combustion included in this study that finally deposits in the Baltic Sea and contributes to
eutrophication there is hard to predict. With punctual emissions, on the other hand, the amount that finally ends up in a specific area is the same as the emission released there. For the studied system in this LCA, the nutrient uptake from the mussels is punctual and only affecting the eutrophication in the Baltic Sea. The conclusion of this is that the actual impact from diffuse eutrophicating emissions from the system in this LCA could be different to the presented result, in that case, the net reduction would also be impacted. The climate change impact category has a global impact which means that these uncertainties do not exist in the same way since that is not a regional impact category.

To adapt the method even further to the specific geographical boundaries for this study, the freshwater eutrophication and marine water eutrophication impact categories were combined. This is due to the fact that the Baltic Sea is said to be both N- and P-limited and therefore both N- and P-compounds can contribute to eutrophication and need to be considered. If only one substance would be considered, the eutrophicating impact from the system would be underestimated.
11 Conclusion

In this chapter the conclusions for this study and possible future studies will be presented.

- Even when including the material and energy use of the farm, there is a net reduction of nitrogen and phosphorus which results in a reduction of eutrophication of -1383 kg N-equivalents for Scenario 1 – Mussel farm. However, with this nutrient reduction comes an impact on climate change of around 13 tonnes CO₂-equivalents. Comparison to other similar studies show that the environmental performance for the mussel farm depends on the farming technique, the primary function of the farm (human consumption or environmental measure) and the modelling principles.
- Scenario 3 – Biogas has the biggest reduction of eutrophication and smallest contribution to climate change compared to all other scenarios, even when including only the mussel farm.
- When including the transport and production of the different mussel products, the net reduction of eutrophication is not majorly affected compared to only the mussel farm itself. However, the contribution to climate change is affected and varies significantly between the three mussel products.
- An upscaling of the mussel farm to commercial size makes it more energy efficient which reduces the climate change impact per tonne mussels. The material used per tonne mussels, on the other hand, is not significantly affected.
- The transport has a significant impact on the overall environmental performance, where the distance, type of fuel and way of transportation influences the impact.
- If the result is normalized with an average European as reference, the reduction of eutrophication is greater than the contribution to climate change for the mussel farm itself and regardless of which mussel product that is produced. However, this does not indicate which of the impact categories that is of most importance without subjective assessment.

For future studies it is of interest to do LCA on other farms to validate the result further and also to include a comparison of different farming techniques and locations. Furthermore, an inclusion of more impact categories, for example marine toxicity, would be beneficial for a more complete environmental assessment. To fully be able to decide about mussel farming as a tool for mitigating eutrophication, an economic analysis of the mussel farms need more research as well as comparison with other mitigation strategies.
References


Baltic EcoMussel project (2013) Mussel farming the new baltic Sea aquaculture industry.


Nordell, E. (2018) ‘Development Engineer at department Biogas R&D at Tekniska Verken Linköping AB, mail contact’.


Palm, O. (2018) ‘Section Manager at Research Institutes of Sweden, mail contact’.


god miljö och hälsa samt ny sysselsättning i skärgården. Available at:
https://www.havochvatten.se/download/18.64f5b3211343cfaddb2800022568/1348912826217/mus

circular economy: Alternative concepts for trans-disciplinary research’. doi:


Stadmark, J. and Conley, D. J. (2011) ‘Can musselodling rena Östersjön?’, Havsnöt. Available at:


Steffen, W., Richardson, K., Rockström, J., Cornell, S. E., Fetzer, I., Bennett, E. M., Biggs, R.,
Carpenter, S. R., de Vries, W., de Wit, C. A., Folke, C., Gerten, D., Heinke, J., Mace, G. M., Persson, L.

Svensk biogas (2018) Frågor och svar / Svensk Biogas. Available at:

Svenskt Vattenbruk (2017) Musselodling - Vattenbruk. Available at:

Sveriges miljömal (2018) Ingen övergödning - Sveriges miljömal. Available at:


Trafikverket (2018) Underlagsrapport till Inriktningsunderlag 2018-2029 - Sjöfart. Available at:
2018).

Vidaković, A. (2015) Fungal and Mussel Protein Sources in Fish Feed: Nutritional and Physiological


Appendix

In this Appendix the results is presented numerical.

Table A 1. Results for each scenario in the eutrophication and climate change impact categories respectively presented for both 1 harvest from St. Anna and for 1 tonne mussels.

<table>
<thead>
<tr>
<th>St. Anna farm 1 harvest</th>
<th>Eutrophication [kg N-equivalents]</th>
<th>Climate Change [tonne CO₂-equivalents]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scenario 1</td>
<td>Scenario 2</td>
</tr>
<tr>
<td>Mussels</td>
<td>-1 431,4</td>
<td>-1 431,4</td>
</tr>
<tr>
<td>Material farm</td>
<td>10,9</td>
<td>10,9</td>
</tr>
<tr>
<td>Energy use farm</td>
<td>37,9</td>
<td>37,9</td>
</tr>
<tr>
<td>Transport</td>
<td>-</td>
<td>45,3</td>
</tr>
<tr>
<td>Material production</td>
<td>-</td>
<td>3,7</td>
</tr>
<tr>
<td>Energy use production</td>
<td>-</td>
<td>20,4</td>
</tr>
<tr>
<td>Avoided products</td>
<td>-</td>
<td>-7,4</td>
</tr>
<tr>
<td>Compost emissions</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>-1 382,6</td>
<td>-1 320,6</td>
</tr>
</tbody>
</table>

1 tonne mussels

<table>
<thead>
<tr>
<th>Eutrophication [kg N-equivalents]</th>
<th>Climate Change [kg CO₂-equivalents]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>Scenario 2</td>
</tr>
<tr>
<td>Mussels</td>
<td>-19,0</td>
</tr>
<tr>
<td>Material farm</td>
<td>0,15</td>
</tr>
<tr>
<td>Energy use farm</td>
<td>0,5</td>
</tr>
<tr>
<td>Transport</td>
<td>-</td>
</tr>
<tr>
<td>Material production</td>
<td>-</td>
</tr>
<tr>
<td>Energy use production</td>
<td>-</td>
</tr>
<tr>
<td>Avoided products</td>
<td>-</td>
</tr>
<tr>
<td>Compost emissions</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>18,35</td>
</tr>
</tbody>
</table>

Table A 2. Results from the sensitivity analysis of Scenario 1 – Mussel farm in the eutrophication and climate change impact category, presented for 1 tonne mussels

<table>
<thead>
<tr>
<th>Eutrophication [kg N-equivalents]</th>
<th>Climate Change [kg CO₂-equivalents]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Worst</td>
<td>Modest</td>
</tr>
<tr>
<td>Mussels</td>
<td>-19</td>
</tr>
<tr>
<td>Material Farm</td>
<td>0,15</td>
</tr>
<tr>
<td>Energy farm</td>
<td>0,5</td>
</tr>
<tr>
<td>Total</td>
<td>-18,35</td>
</tr>
</tbody>
</table>
Table A3. Results from the sensitivity analysis of Scenario 2 – Mussel meal, Scenario 3 – Biogas and Scenario 4 – Compost in the eutrophication and climate change impact category, presented for 1 tonne mussels and only the impact for the transportation is presented.

<table>
<thead>
<tr>
<th>Name on variation</th>
<th>Location production site</th>
<th>Way of transportation</th>
<th>Eutrophication [kg N-equivalents]</th>
<th>Climate Change [kg CO2-equivalents]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 2</td>
<td>Tromsø, Norway</td>
<td>Fossil fuelled truck</td>
<td>0,60</td>
<td>479,9</td>
</tr>
<tr>
<td>Scenario 2a</td>
<td>Tromsø, Norway</td>
<td>Non-fossil fuelled truck</td>
<td>4,66</td>
<td>191,0</td>
</tr>
<tr>
<td>Scenario 2b</td>
<td>Limfjorden, Denmark</td>
<td>Fossil fuelled truck</td>
<td>0,31</td>
<td>244,9</td>
</tr>
<tr>
<td>Scenario 2c</td>
<td>Limfjorden, Denmark</td>
<td>Non-fossil fuelled truck</td>
<td>2,38</td>
<td>97,4</td>
</tr>
<tr>
<td>Scenario 2d</td>
<td>St. Petersburg, Russia via Västervik</td>
<td>Fossil fuelled truck + heavy fuel oil cargo ship</td>
<td>0,15</td>
<td>47,2</td>
</tr>
<tr>
<td>Scenario 2e</td>
<td>St. Petersburg, Russia via Västervik</td>
<td>Non-fossil fuelled truck + natural gas cargo ship</td>
<td>0,31</td>
<td>33,6</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>Linköping, Sweden</td>
<td>Fossil fuelled truck</td>
<td>0,03</td>
<td>21,2</td>
</tr>
<tr>
<td>Scenario 3a</td>
<td>Linköping, Sweden</td>
<td>Non-fossil fuelled truck</td>
<td>0,21</td>
<td>8,4</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>Högybytorp (Stockholm), Sweden</td>
<td>Fossil fuelled truck</td>
<td>0,08</td>
<td>67,2</td>
</tr>
<tr>
<td>Scenario 4a</td>
<td>Högybytorp (Stockholm), Sweden</td>
<td>Non-fossil fuelled truck</td>
<td>0,65</td>
<td>26,7</td>
</tr>
<tr>
<td>Scenario 4b</td>
<td>Kil (Karlstad), Sweden</td>
<td>Fossil fuelled truck</td>
<td>0,10</td>
<td>78,4</td>
</tr>
<tr>
<td>Scenario 4c</td>
<td>Kil (Karlstad), Sweden</td>
<td>Non-fossil fuelled truck</td>
<td>0,76</td>
<td>31,2</td>
</tr>
<tr>
<td>Scenario 4d</td>
<td>Zero transportation</td>
<td>-</td>
<td>0,00</td>
<td>0,0</td>
</tr>
</tbody>
</table>