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– recalculation of the inventory assessments

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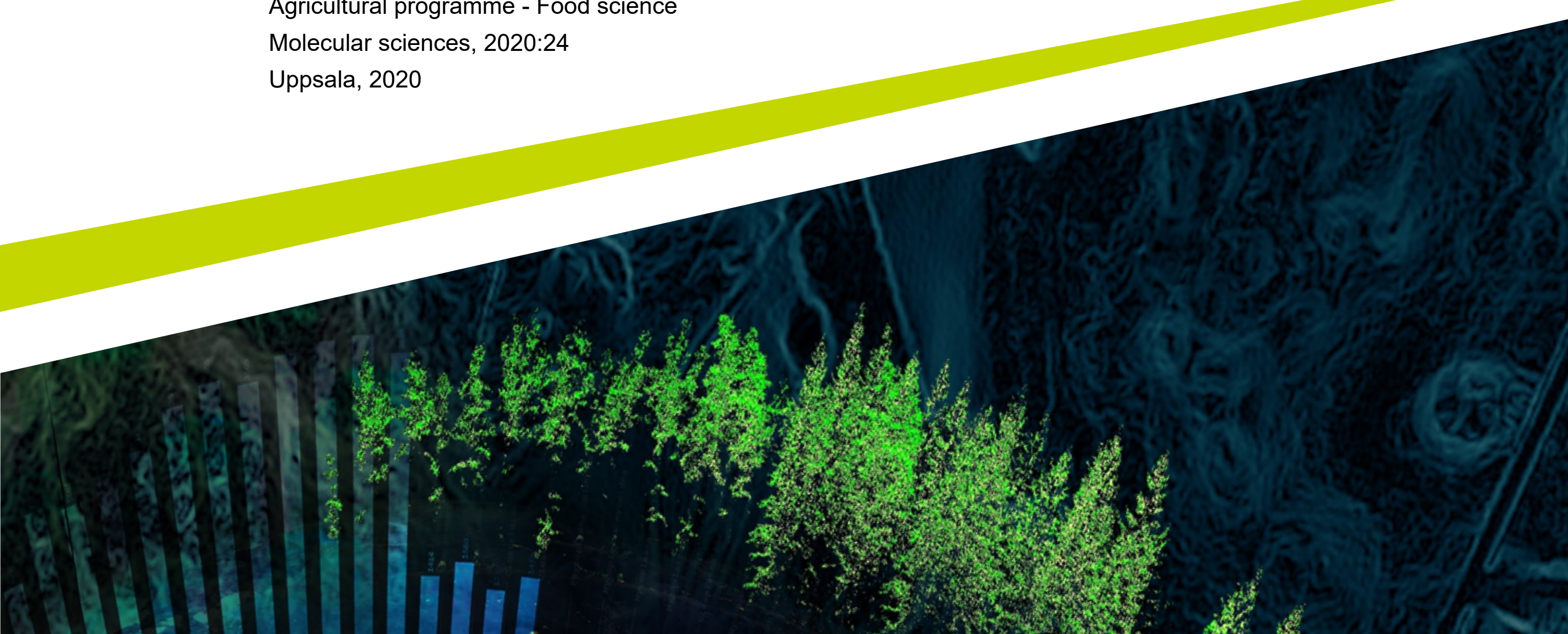

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Abstract

With a growing world population there is an increased demand of sustainable and nutritious food. There is not much more land to farm on whether for food or for feed for livestock. Aquaculture increases more than any other production method, however there is still often a need for feed. Mussels are low trophic species that grow without input of feed, additives and antibiotics. They are filter feeding organisms consuming planktonic particles. Therefore, when harvested, nutrients are removed from the environment, reducing eutrophication. Life cycle assessment is a standardised method of calculating environmental impact.

The goals of this thesis were to compile life cycle assessments about cultivated blue mussels through a literature review and to recalculate the carbon footprint and the marine eutrophication potential. The inventory assessments of six published mussel LCA studies and one dataset were analysed. Harmonization of methodologies was performed and a uniform functional unit of **one tonne of Blue mussels produced** was chosen.

The recalculation resulted in a mean of 0,95 kg CO_2-equivalents/kg mussel with shells at harvest and 5 mg N-equivalents/kg produced of mussels with shells at harvest. Hotspots identified were production of material used in cultivation, followed by energy and fuel use. Even though mussels have a low environmental impact, using more energy efficient boats or farmers sharing vessels could further reduce the emissions. Mussels have a high nutritional value and are relatively sustainable, making them an interesting future food product or ingredient in new products.

Keywords: Blue mussels, LCA, compilation, sustainability, production

Sammanfattning

Med en växande världsbefolkning krävs det mer hållbar och nyttig mat. Det finns dock inte mycket mark kvar för odling, varken för humankonsumtion eller för foder. Akvakultur är den produktionsmetoden som ökar mest, dock ofta med ett behov av foder. Blåmusslor är lågtrofiska organismer som odlas utan tillsats av vare sig foder eller antibiotika. De lever av att filtrera plankton och andra partiklar. Vid skörd tas näring med upp från havet, vilket minskar övergödningen. Livscykelanalys är en standardiserad metod för att beräkna miljöpåverkan. I den här rapporten har klimatavtryck och övergödningspotential undersökts.

Syftena med denna uppsats var dels att sammanställa livscykelanalyser om musselodling genom en litteraturundersökning samt att räkna om klimatavtrycket och den marina övergödnings-potentialen. Sex publicerade mussel-LCA-rapporter och ett data set analyserades för deras inventarieanalys. Harmonisering av metoder genomfördes och den gemensamma funktionella enheten av **ett ton odlad blåmussla** valdes.

Musslor gav i snitt upphov till utsläpp av 0,95 kg CO_2-ekvivalenter/kg mussla med skal vid skörd och 5 mg N-ekvivalenter/kg mussla med skal vid skörd. ”Hotspots” som identifierades var produktion av material följt av energi- och bränsleanvändning. Trots att musselodling har låga utsläpp skulle användning av mer energieffektiva båtar, användning av förnybar el eller att odlare delar på utrustning minska miljöpåverkan ytterligare. Musslor har högt näringsinnehåll och är jämförelsevis hållbara vilket gör dem till ett attraktivt framtida livsmedel eller ingrediens i nya produkter.

Nyckelord: Blåmusslor, LCA, sammanställning, hållbarhet, produktion

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Abbreviations

LCA	Life cycle assessment
LCI	Life cycle inventory
FU	Functional unit
GWP	Global warming potential
CF	Carbon footprint
CO_2-eq	Carbon dioxide equivalent
EP	Eutrophication potential
ME	Marine eutrophication
PO_4^{3-}eq	Phosphate equivalent
N-eq	Nitrogen equivalent
CED	Cumulative energy demand
CS	Carbon sequestration
PDO	Protected designation of origin
GHG	Green-house gas
GHGE	Green-house gas emission

1. Introduction

This introduction section describes the production of mussels, gives information about life cycle analysis (LCA) and motivates the objective of this thesis.

1.1. Mussel production in a global perspective

With a growing world population more food is needed but there is not much more land to farm on, at the same time wild fish populations are becoming depleted. Today's agriculture uses 43% of the world's desert- and ice-free land (Poore & Nemecek 2018).

The aquaculture sector has increased (FAO 2018), a lot more than any other food sector. Livestock production increased with an average of 2,5 % per year between 1993-2013 (Hilborn et al., 2018). This can be compared to the aquaculture sector that increased with an average of 5,8 % per year between 2009 to 2014. During the same period, the capture fisheries have levelled out (Hilborn et al., 2018), (Figure 1). However, the need for feed in fed aquaculture of high-trophic species, is still great and that either requires land for farming or wild fish for fish meal and fish oil.

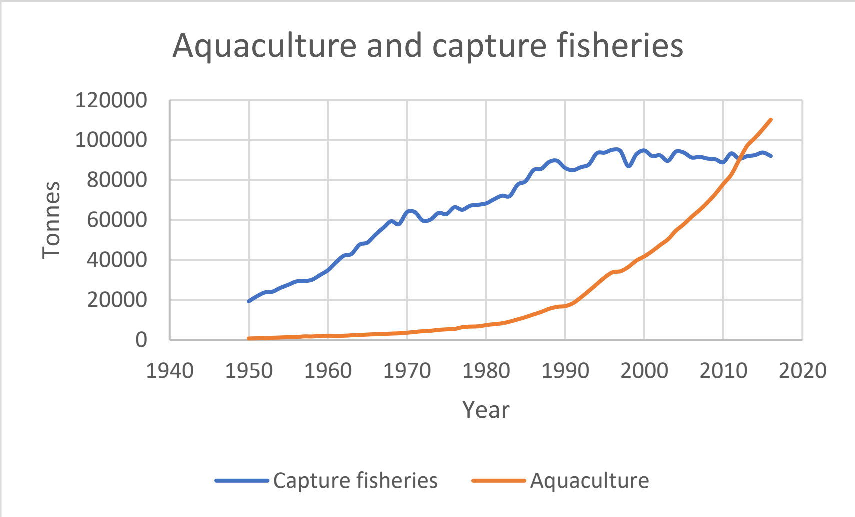

Figure 1. Tonnes fish caught and produced globally since the 1950's (FAO 2020)

Instead, low trophic aquaculture of species that grow without input of feed, additives or antibiotics, could be further cultivated (Cajas de Glinwicz 2016). Low trophic aquaculture includes algae and bivalves, high trophic species are for example salmon. Bivalves are a phylum within the molluscs which consist of families such as oysters and mussels.

Between the years 2010-2015, a mean of 15 million tonnes of marine bivalves were produced globally annually, 89% of which were cultivated (Wijsmann et al., 2019). China is the biggest producer, accounting for 85% of the production. Mussels stand for 13% of the global bivalve production, compared to oysters which stand for 33%.

Blue mussels (*Mytilus edulis*) are an important bivalve in Europe (Wijsmann et al., 2019), which have been harvested for 8000 years (FAO 2020). The production is decreasing in Europe, mainly due to a decrease in bottom culture in the Netherlands (Wijsmann et al., 2019). Blue mussels are tolerant to environmental factors, enabling their wide distribution in different habitats. They occur naturally along the Atlantic coast from southern France to Russia (FAO 2020), with variance in water salinity and temperature in their wide geographic distribution,. When assessing the financial aspects of mussel cultivation, the main expenses were labor, seed supply and professional expenses (Cajas de Glinwicz 2016).

Bivalves are filter feeding organisms, consuming phytoplankton and other organic particles. Instead of addition of feed, water quality is critical (Rosengren 2017). Feed is otherwise a major cost during aquaculture as well as a source of waste, (Ziegler et al., 2013) as unutilized feed and faecal matter is accumulating under the fed fishes. The filtration capacity depends on the size of the mussels, temperature, particle concentration and currents and waterflow (Lindahl et al., 2004). Filtration can reduce the risk of harmful algal blooms (Cajas de Glinwicz 2016). When filtering, water quality is improved, and eutrophication is reduced as nutrients are removed. The removal of particles allows more light to penetrate the water body which allows bottom-living algae to grow and produce oxygen. It further reduces the sedimentation and the oxygen consumption (Lindahl et al., 2004), as it can mitigate habitat degradation due to low dissolved oxygen levels from otherwise accumulating decomposing organic matter (Cajas de Glinwicz 2016). Locally however, there is increase in organic matter (Lindahl et al., 2005) and reduced biological diversity (Lindahl et al., 2004) due to the faeces and pseudo-faeces.

Besides the provisioning aspects of food, feed and fertilizers, mussel cultivation provides ecosystem services, increasing both the environmental and economic importance (van der Schatte Olivier et al., 2018). Supporting services include increased biodiversity, formation of reefs and new habitats and new sediment from faeces and pseudo-faeces. Sheehan et al. (2019) found that suspended ropes in a mussel farm in south west England, increased the biodiversity of both fish in the water column and crustaceans on the seabed. As compared to areas without mussel production. There are also cultural aspects regarding tourism and employment as well as traditional foods. Regulating services provided are carbon sequestration and removal of nutrients. Mussels remove more nitrogen and phosphorus per tonne shellfish produced compared to other bivalves (van der Schatte Olivier et al 2018), 1,4% and 0,14% per live weight respectively, (Cajas de Glinwicz 2016). Harvesting of one ton of blue mussels can remove 27,7-44,7 kg carbon, 6,4-10,2 kg of nitrogen and 0,4-0,6 kg of phosphorus (Lindahl et al., 2004).

A 100 g portion of Blue mussels contains 24 g protein, 56 mg cholesterol and 4,5 g of total fats (Cajas de Glinwicz 2016). They are rich in omega-3 fatty acids and iron and calcium. One portion of mussels provides the consumer with the daily recommended intake of both iodine and selenium (Livsmedelsverket 2012). Mussels can also be used as chicken feed (Henriksson & Ståhle 2019).

There are also risks and negative aspects connected to large-scale bivalve cultivation, as for example depletion of natural plankton concentration and changes in nutrient and oxygen fluxes (Aubin et al., 2018). There is also an increased risk of invasive species and diseases as bivalves can be vectors. Pacific oysters *Crassotrea gigas* introduced for cultivation in France further brought 57 macroalgal taxa (Aubin et al., 2018). The benthic ecosystem receives an increased load of organic material locally from the faeces. This might cause chemically reduced sediments and decreased oxygen concentration and asphyxia (Lindahl et al., 2005). The degree of influence depends on depth, bottom topography and currents. The hydrology, currents and tidal impact, affects the deposition and dilution rate of accumulated waste (Aubin et al., 2018). Cultivation in closed areas can increase waste accumulation and reduce local biodiversity (Sheehan et al., 2019, Lindahl et al., 2004).

There are risks connected to consumption of mussels such as food poisoning from bacteria and virus or algal toxins as well as consumption of heavy metals. Bacteria and viruses die or are inactivated during heating, algal toxins are often heat-stable and remain poisonous (Rosengren 2017). Presence of *E. coli* bacteria is an indication of faecal contamination and indicates risk of increased levels of viruses (Rosengren 2017). Depuration, a filtering cleaning step after harvest, decreases the level of algal toxins (Rosengren 2017). To increase the reliability of mussels, food safety issues due to biotoxins and environmental contaminants should be minimized (Wijsmann et al., 2019). Mussels can only be sold for consumption as food and feed if they origin from controlled areas, a label that shows that they are controlled is required (Beckman Sundh and Toljander 2017).

Mussel have, thus, a huge potential as a mean for mitigating eutrophication through the removal of nutrients. But the negative impacts and risks are also important aspects that need to be addressed.

1.2. Production systems

Mussels can be cultivated differently, three common techniques are, *Bouchot, suspended rope culture* and *bottom culture*. The general steps of mussel cultivation are: spat collection/attachment, grow-out and harvest. Spat is young larval mussels. After fertilization in the spring the mussel larvae have a free-swimming phase until they attach to a suitable surface with the byssus thread (Lindahl et al., 2004). The naturally occurring juveniles are often enough for suspended cultivation (Frösell 2019). However, juveniles are sometimes collected from other areas (Aubin et al., 2018) for Bouchot and bottom cultivation. Processing steps that follow include, but are not limited to, depuration, grading, sorting, boiling and canning or freezing. After harvest, mainly three types of sectors are responsible for the processing (Iribarren et al 2010), dispatch centres, canning factories and cooking plants.

Depuration is the "cleaning" after harvest in clean or sterilized water (can be UV-treated) the mussels filters out the waste, biological contaminants (bacteria and/or toxins) and physical impurities (sand) (Meyhoff-Fry 2012). Depuration is not always required but depends on the area which can be classified as clean or contaminated, depending on presence of *E. coli* bacteria, an indication of faecal matter (Wijsmann et al., 2019) or due to toxic algal blooms.

The harvesting size of blue mussel is around 5 cm, which is reached in 2-3 years (FAO 2014). The desired size varies between different markets and countries (Persson 2020). The growth rate depends on the phytoplankton availability in the water (Meyhoff-Fry 2012), and on the salinity, mussels in saltwater grow bigger than those in freshwater (Rosengren 2017). Submerged mussels grow faster than those who are exposed to air during tidal fluctuations (Cajas de Glinwicz 2016).

Bouchot

Is common in France, wooden poles, so called "bouchots", are fixed on the seabed in the shallow inter-tidal zone and used as supports onto which mussel spat are transplanted for on-growing (FAO 2014). Spat can be collected from elsewhere than where the poles (the bouchots) are located, if the poles are in an area where naturally occurring spat are low in abundance. Bouchot mussels have the French label of “protective designation of origin” (PDO). This PDO specification restricts the maximum numbers of bouchots used at the same time, to preserve the productivity of the bay (Aubin et al 2018). The poles are often made of tropical wood, which have a lifespan of 15 years, and are presumed to be rot resistant after use and can be re-used in landscaping. The mussels are often supported with nets and reach a harvestable size in eight months. During harvest, the wooden stakes are scraped with amphibious boats and hydraulic arms (Aubin et al., 2018).

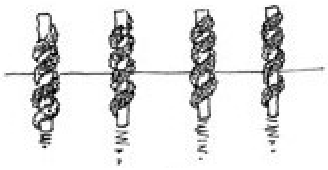

Figure 2. Bouchot culture (FAO.org 2009)

Suspended rope culture

Suspended rope culture is the most common technique in areas where the sea is too deep for the other systems, in Sweden, Spain, Ireland and Norway for example (FAO 2014). The spat settlement occurs in the spring, the high abundance of larvae in the water attach to the ropes or nets and start to grow (Frösell 2019). The ropes or nets can be suspended either from rafts, wooden frames or long lines attached to buoys. The longline method was developed in Sweden in the 1980’s, one production unit producing 120 tonnes of mussels every other year at an area of 0,4 hectare (Lindahl et al., 2004). A too high density impairs the waterflow and the growth of the mussels, and many would drop to the bottom (Frösell 2019). If the density is too high, the mussels can be thinned to promote optimal growth (FAO 2014, Meyhoff-Fry 2012, Frösell 2019). During thinning, special equipment is used, rotating drums, conveyors and grading machines. The same equipment is used during harvest (Meyhoff-Fry 2012).

Suspended cultivation can be placed offshore, which is seen as more space efficient with less competition, as compared to cultivation closer to shore (Sheehan et al 2019). However, the profitability of offshore production has not yet been proven (FAO 2014). Cultivation closer to shore results in lower fuel use (Meyhoff-Fry 2012).

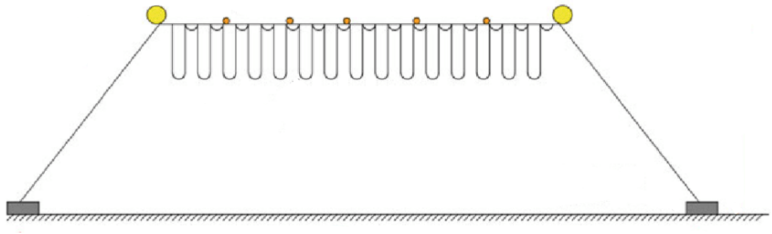

Figure 3. Schematic picture of a longline systems (Adapted from Goseberg et al., 2017)

Bottom culture

In bottom culture, spat is collected from the wild and placed onto more favourable plots. The plots are managed to remove predators, and mussels can be moved between inter- and subtidal areas to receive optimal growth. Market size (45 mm) is reached within 2-3 years. Harvest is done through dredging or manually. This technique is common in the UK, the Netherlands and Germany (FAO 2014). Dredging during harvest, has a higher fuel consumption as compared to suspended rope cultivation (Hallberg 2018).

Dredging in a Danish strait showed fewer species within the mussel beds which lasted for 40 days (Dolmer et al., 2001), however there was an increase in number of species just outside the dredged mussel bed. Dredging further disturbed the mussel bed which resulted in reduced growth and density of mussels, it further disturbed the filtration of the non-removed individuals. The impact of the dredging depends on the sediment type.

1.3. Background to LCA

LCA is a standardized tool (ISO 14040 series) to assess a product's environmental impact through its lifetime (Baumann & Tillman 2004). There are four steps of an LCA; the *goal and scope definition*, the *inventory analysis*, the *impact assessment* followed by the *interpretation*. There are four issues and implications that the reader of an LCA report should be aware of (Baumann & Tillman 2004); the definition of the functional unit, system boundaries & allocation, type of data used and how the impact assessment is made.

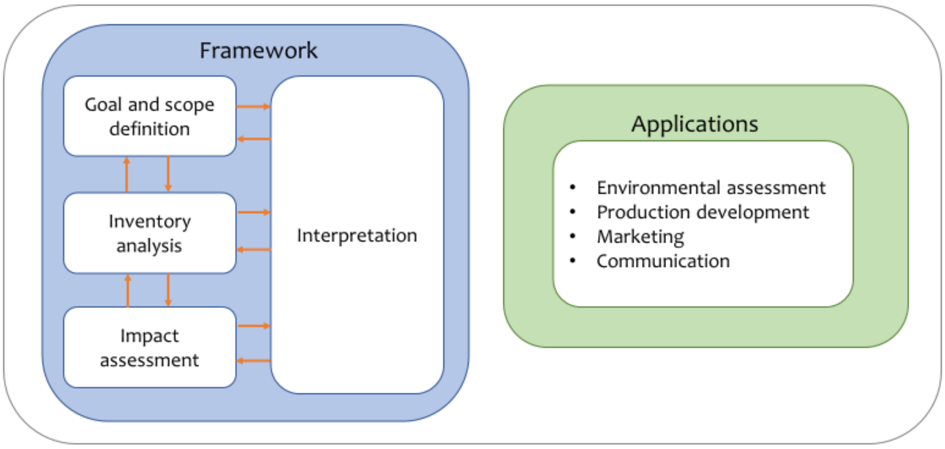

Figure 4. The LCA framework and proposed applications connected to mussel cultivation (Adapted from Baumann and Tillman 2004)

In the *goal and scope definition* phase, answering the questions of *who* wants to and *why* the assessment should be made, are important for the aim and goal. Choosing the functional unit, method and system boundaries (geographical, natural systems, time, production capital/personnel, allocation, division of systems etc.) are important to further set the aim (Baumann & Tillman 2004). "Cradle to grave" and "cradle to gate" are concepts of defining "how far" the assessment analyses (Meyhoff-Fry 2012). Cradle to grave includes the consumers whereas the cradle to gate stops at the gate of the production plant. The impact categories are chosen in this phase.

During the *inventory analysis* phase a flow chart is often set up to further visualise the system. Data collection and calculations are also included. During the *impact assessment* the inventory phase is translated into environmental impact. The result is classified and characterised for facilitated comparison. The *interpretation* includes presentation of the results. It often includes hot spots as the most polluting, the robustness of the result and sensitivity analysis, consistency of methodological choices for example (Baumann & Tillman 2004). The result from the LCA can be used for environmental assessment, production development, marketing and communication (Meyhoff-Fry 2012).

1.3.1. Impact categories

The impact categories are chosen in the goal and scope phase. The goal of the impact assessment is to describe the environmental consequences of the production (Baumann & Tillman 2004). A part of the impact analysis consists of characterization methods of impact categories which aims to translate the emissions. Here follow some impact categories which will be of importance in this thesis. It is, however, not a complete list over all impact categories that exists.

Acidification potential (AP)

A pollutant that releases H^+ ions, increases the acidity in the environment. Examples of impact are; damage to buildings and forests, leaching of toxic metals from the soil and rocks and increased fish mortality (Baumann & Tillman 2004). The impact of the acidification depends on the environment and its ability to buffer (Baumann & Tillman 2004). Mussels are affected by acidification through altered carbonate saturation (Fitzer et al., 2015) this impairs the shell formation which affects the protection against predators and changes in the environment. The unit for AP is SO_2-equivalents.

Eutrophication potential (EP)

Eutrophication affects the biological productivity as there generally is an increase of nutrients (N and P) into the environment. Increased productivity often leads to increased oxygen consumption which has further implications on the environment (Baumann & Tillman 2004). Mussels generally have a negative EP as nutrients are removed at harvest, through their filtrating of plankton. The unit for assessing marine eutrophication is N-equivalents which results in a somewhat lower impact than when assessing freshwater eutrophication where PO_4^{-3}-equivalents is used.

Carbon footprint/Global warming potential (CF/GWP/GHG)

The emission of green-house gases (GHG) is measured in CO_2-equivalents. GHGs are responsible for the warming of the earth's surface which has impacts on the environment and the climate change. Emissions of CO_2 during respiration should not be included as a GHG (Ray et al., 2018), as it is seen as a recycling of CO_2 from photosynthesis, in a short life cycle. Carbon sequestration (CS) is not categorized as a characterization method according to Baumann and Tillman (2014). It is however an important aspect of mussel cultivation.

1.4. LCA and blue mussels

LCAs can enhance the transparency and accountability of the mussel production (Iribarren et al 2010). Meyhoff-Fry (2012) concludes reasons for assessing the carbon footprint; it identifies hotspots which, when further analysed, can lead to development of more sustainable cultivation methods and vessels. Thus, reducing the future emissions LCAs could further be a basis to develop criteria for sustainable farming as well as facilitate collaboration and communication between companies and farmers. Thirdly it could be a basis for marketing and for information to consumers (Meyhoff-Fry 2012).

The problem and difficulties of reviewing blue mussel LCAs are firstly the lack of data existing in the handful of studies that have been done, compared with other species. Secondly, the assessments that exist often analyse one farm using a functional unit that might not be easily compared to other production systems, and may have other methodological difference (system boundaries, data sources, time perspective) that leave results largely incomparable. A systematic review and a harmonization of functional unit and other methodological choices is needed.

1.5. Objective

The main objective of this thesis was to review LCA literature of farmed blue mussels with the goal of providing a current report of what data exists. A second objective was to harmonize methodologies of published and unpublished datasets and to re-calculate the results, to reach more comparable results. These were used for the third objective, to evaluate which conclusions can be drawn about the life cycle impacts of farmed blue mussels, and whether differences between production techniques can be identified.

2. Methods

The focus of this thesis was on cultivated blue mussels, *Mytilus edulis.* The thesis was divided into two sections, the first one, a compilation of existing LCAs through a literature search. The reports and theses found were mainly analysed for the methodologies and conclusions. The second part consisted of recalculating the inventory assessments. To facilitate the comparison, harmonization of the; FU, allocation and system boundaries and choice of background data were performed.

2.1. Literature review

A screening of a database (Google scholar) was conducted. The criterion for the articles were *the correct species (Mytilus edulis)* and that the inventory assessment should be easily accessible for a recalculation. Two student theses were found on google scholar Frösell (2019), and Henriksson & Ståhle (2019), as well as Aubin (2018) and Meyhoff-Fry (2012). Hallberg (2018) and Winther et al. (2009), as well as the unpublished dataset (Thomas et al., in prep) was provided by the supervisor of this project.

The studies by Hallberg (2018), Aubin (2018) and Meyhoff-Fry (2012) analyses more than one functional unit for comparison. Aubin (2018) is the only one assessing bouchot mussels. No study on bottom culture was included due to inability to find one.

Table 1 gives an overview of the cases reviewed, production method, their FUs and what impact categories that were assessed. The most common assessed impact category is carbon footprint. See appendix I for information about the evaluated cases.

Table 1. Compilation of publications reviewed. The functional unit and which impact categories that are studied. CED= cumulative energy demand

Case	Method	FU	AP	EP	CF	CS	CED
Frösell 2019	Suspended	1 kg of edible meat		✓	✓		
Hallberg 2018	Suspended	1 kg live weight **and** 1kg edible meat		✓	✓		
Aubin 2018	Bouchot	1 ton ready to cook **and** 1 tonne edible protein	✓	✓	✓	✓	✓
Meyhoff-Fry 2012	Suspended	1 tonne product **and** 500 g serving			✓	✓	
Thomas et al in prep	Suspended	1 tonne fresh weight		✓	✓		✓
Winther et al 2009	Suspended	Kg raw product			✓		
Henriksson & Ståhle 2019	Suspended	1 tonne fresh weight		✓	✓		

2.2. Recalculation of reviewed LCAs

An LCA was performed to analyse and compile the environmental impact of the inventory assessments from the cases described in section 2.2.

Goal and scope definition

The goal of this LCA was to compile the inventory data of the previous LCAs and harmonize methodologies to see if general conclusions can be drawn. The intended audience is the mussel industry. Focus is the emissions of production and to highlight differences in the production.

System boundaries

The system boundary was “cradle to gate”, including the steps from spat collection to harvest. The production of material and energy use at the production site and on land during harvest was included. The post-harvest losses, cooking and processing steps as well as the capital burdens were excluded. Capital burdens are the production and maintenance of machinery used it can also be the commuting of personnel (Baumann & Tillman 2004). Nutrient uptake and carbon sequestration might vary between the production sites and have not been assessed as focus have been to assess the emission of the production.

Functional unit

A uniform functional unit, **one tonne produced fresh weight**, with shells, was chosen to facilitate comparison between the different cases. The fresh weight was assumed at landing after harvest. This can be at a barge at sea or at land and varies between the production method of the cases.

Inventory assessment

The inventory assessments from the cases presented in table 1, were extracted from the publications. From the database Ecoinvent, data for the best fitting material was extracted for the impact categories of global warming potential (GWP) and marine eutrophication (ME). The values from Ecoinvent was multiplied with the amount of material used per tonne produced. The characterisation method used was "ReCiPe 2016 v1.1 midpoint method, hierarchist version". See appendix II for the values extracted from Ecoinvent.

Harmonization of materials and lifetime

Instead of finding the exact material used in each farm site and in the LCIs, the same material was chosen between the different farms, e.g. for plastics, steel, fuel in the recalculation. The intention was to receive a comparable result and to be able to see the differences between the different production systems and farms, minimizing the variation in materials used. For example, for metal, steel-low alloyed was chosen for all farms instead of iron. (See appendix III for the compiled inventory data). A further harmonization choice was the assumption of similar lifetime per the material, a mean of the lifetimes assessed was chosen. See appendix II for the emission per material and fuel per the Ecoinvent database and per the lifetime with the reference.

3. Results

The result section is divided into two parts, the hotspot analysis based on the literature review and the recalculation of the LCIs.

3.1. Hotspots

The two main hotspots for climate impact are the farm operations and production of materials, this is true independent on the system boundaries. Farm operations includes fuel and electricity use. Meyhoff-Fry (2012) found that farm operations and material production stands for 60% and 40 % of the CO_2-eq per tonnes product respectively. If depuration is included, it contributes with 6,6 % of the emissions. Both Frösell (2019) and Hallberg (2018) found in their assessments of farms in Sweden and Denmark that the energy use at harvest was a hotspot and that the big bags used had the individual biggest impact per material, when assessed as disposable when used for shipping after harvest.

The different culture methods affect the fuel consumption. Aubin et al. (2018) concludes that the use of fuel intensive amphibious vehicles in Bouchot culture increases the fuel use and energy demand. Bottom culture with dredging has a higher fuel consumption than suspended cultivation (Hallberg 2018). Cultivation closer to shore results in lower fuel use (Meyhoff-Fry 2012).

3.2. Recalculation of life cycle impacts

Table 2 and 3 show a compilation of the amount of material and fuels used per tonne mussels produced in the different cases. The different types of plastic are used for nets and ropes, concrete and steel are used for anchoring and wood is used in the poles in the bouchot culture. Cotton nets are material with a high environmental impact, and are used in the assessments made by Frösell, Meyhoff-Fry and Aubin. The most common plastic used is polypropylene. These tables further show the variation in material used in the different systems. Transportation has been assessed by Thomas et al. (in prep) and is included in fuel and energy use in the recalculation in table 5. Table 2 and 3 further shows the variance among the cases of the amount used.

Table 2 Compilation of the amount of material, recalculated per tonne Blue mussels produced

	Material							
	Kg material/ton Blue mussels produced							
Cases	**Poly-propylene**	**Poly-uretan**	**Polyinvyl-chloride**	**Poly-ethylene**	**Steel**	**Concrete**	**Wood**	**Cotton**
Hallberg	2,6				0,0007	0,05		
Thomas W	0,2			0,8	0,8			
Thomas E			0,6	1,8	0,1	120,0		
Winther	0,3				0,4			
Frösell	93,2	0,3	0,003	7,3	0,6			1,2
Meyhoff-Fry	0,6			0,5				2,3
Aubin	11,7						0,08	2,7
Henriksson and Ståhle	2,6				0,07	50,9		

Table 3. Compilation of the amount of fuel and transport used per the different units per tonne Blue mussels produced

	Fuel and energy use				Transport
	kg/ton		MJ/ton		tkm
Cases	Heavy fuel oil	Diesel	Electricity	Petrol	Barge and tractor
Hallberg	2,1	50,1	11,4	2,4	
Thomas W		2,7			6,7
Thomas E		2,7			10,3
Winther		47,0			
Frösell		7,8		2485,7	
Meyhoff-Fry		23,3	165,6		
Aubin		39,2			
Henriksson & Ståhle		17,7	396,0		

Table 4 shows the different studies, their FUs and their calculated results, as well as the recalculated result per 1 tonne Blue mussels of fresh weight. The different FU's makes the previous studies difficult to compare. Hallberg (2018) and Meyhoff-Fry (2012) assesses more than one FU. Meyhoff-Fry (2012) further assessed different scenarios with different FUs. In the scenario per ton produced mussels the sequestration and depuration are included, which is not assessed in the present recalculation. In the 500g serving scenario the system boundaries are “cradle to grave”, including assessments of transport to customers and consumption aspects. The system boundaries of this thesis were “cradle to gate” excluding those inputs.

Hallberg, Aubin and Henriksson & Ståhle, assessed the uptake, hence the negative PO_4^{-3} -eq. value, whereas the present recalculation only assesses the emissions. The other cases are assessing freshwater eutrophication, using PO_4^{-3} -equivalents as a unit, whereas in this thesis, marine eutrophication where N-equivalents are used as unit was assessed. N-equivalents gives a lower EP value and cannot be directly compared to the PO_4^{-3} -eq value.

Table 4. The result from the life cycle assessments with their original functional units and the present recalculation of the emissions per harmonized functional unit. The mean and the standard deviation are shown.

		Result		**Recalculated**	
Author	FU	(kg CO2-eq/FU)	(kg PO4-eq/FU)	(kg CO2-eq/ton FU)	(kg N-eq/ton FU)
Hallberg	1 kg live weight	0,072	-0,01	40,56	0,00076
	1 kg of edible meat	2,98	-0,044		
Thomas W	1 ton fresh weight	63,22	0,15	5,85	0,00035
Thomas E	1 ton fresh weight	58,98	0,066	7,83	0,000056
Winther	1 kg raw product	1,7	-	27,56	4,60E-04
Frösell	1 kg of edible meat	0,26	-	281,27	0,0063
Meyhoff-Fry	1 ton produced	251,56*	-	110,42	0,012592
	500 g serving	0,32**	-		
Aubin	1 ton ready to cook	296	-27,7	155,30	0,012526
Henriksson and Ståhle	1 tonne	168,7	-18,35	129,55	7,91E-03
			Mean	94,79	0,0051
			STDAV.P	88,62	0,0051

** Without sequestration and depuration. **Cradle to grave*

The present recalculation resulted in a mean of 95 kg CO_2-equivalents/tonnes mussel and 0,0051 kg N-eq./tonnes mussels at harvest with shells. The values can be translated into 0,095 kg CO_2-equivalents/kg mussel and 5 mg N-equivalents/kg, for easier comparison.

Table 4 further shows that the energy and fuel generally have a higher impact per CF and that material generally have a higher impact on the EP. Bouchot culture, analysed by Aubin, has inverted result from the suspended production, that material have a higher impact than energy and fuels. The standard deviation is lower when excluding the Bouchot mussels from the suspended mussels. The high standard deviation indicates a high variance among the cases.

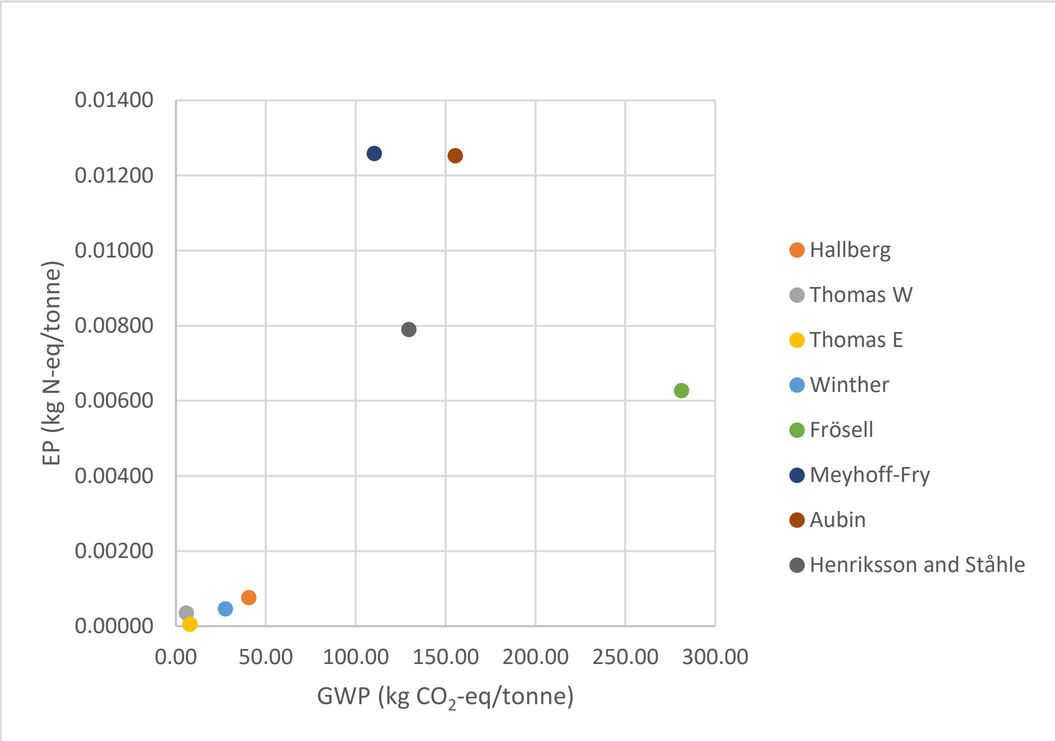

Figure 5. GWP (Global warming potential) and the eutrophication potential per tonne of mussel at harvest in the different cases.

Figure 5 visuals the scattering and the variance in GWP among the cases investigated. Frösell has a high carbon footprint but a quite low eutrophication whereas Aubin and Meyhoff-Fry have a high eutrophication potential but a lower carbon footprint. Frösell's high GWP origins from her high reported fuel use (see table 3). There is a low variance between Hallberg, Thomas W and E and Winther.

Table 5 shows emissions divided per the two identified hotspots, energy and fuel use and production of materials. The total emissions can be seen in table 2.

Table 5. The emissions divided per energy and fuel use and material use per percentage in the evaluated studies per the functional unit.

Emissions	**Energy and fuel**		**Material**	
Case	% CO_2	%N	%CO_2	%N
Hallberg	77,5	80,1	22,5	19,9
Thomas W	35,4	9,2	64,6	90,8
Thomas E	31,2	67,1	68,8	32,9
Winther	93,1	91,4	6,9	8,6
Frösell	78,0	9,9	20,6	90,1
Meyhoff-Fry	29,3	10,5	70,7	89,5
Aubin	11,7	2,4	88,3	97,6
Henriksson and Ståhle	89,3	97,1	10,7	2,9
Mean	**55,7**	**46,0**	**44,1**	**54,0**
SD	29,9	38,9	30,0	38,9
Mean suspended	**62,0**	**52,2**	**37,8**	**47,8**
SD Suspended	26,6	37,6	26,7	37,6

4. Discussion

This discussion chapter will include common themes from the reviewed reports and cases, discussed uncertainties and limitations. Further follows a discussion about the methodology of this thesis as well as a more general discussion about aspects of the production and a comparison with other products. Further some recommendations will be mentioned.

4.1. Uncertainties and study limitations

The general conclusion to draw is that material has a higher impact than energy and fuel use (see table 5). This match the previous findings that mussel production is of low energy requirement and corresponds to Meyhoff-Fry's (2012) result that material production had 60% and fuel and energy use had 40%. The difference to the recalculation is most probably due to the difference in the total emissions, 252 kg CO_2-eq./ ton as compared to 87 kg CO_2-eq./ ton.

There seems to be a general problem of getting producers to report their inventory assessments. Both Winther et al. (2009) (three producers), Meyhoff-Fry (2012) (23% of the Scottish mussels) and Aubin (2018) (four producers) mention that only a small sample of the producers reported numbers. Frösell (2019), Hallberg (2018) and Henriksson & Ståhle (2019) all assessed one farm. Thomas (in prep) reports two Swedish producers, the one on the west coast has several production sites and produces a large share of the Swedish mussels. Data from the east coast was easy to obtain from the producers. The west coast data was obtained from literature, then validated by the producer who said that it was representative of his rigs (Thomas 2020). This can further make it more difficult to draw any conclusions about the representativity of each case. Maybe, pointing at the communicational aspects of LCA's could enhance the farmers interest in reporting primary data. The result from the LCAs can be used for eco-labelling, a positive statement from an independent third party (Baumann & Tillman 2004). Hilborn et al. (2018) states that consumers must have access to transparent information about environmental impact of different foods in order to make a conscious choice.

Meyhoff-Fry (2012) discusses the use of primary and secondary data as study limitations. Primary data is reported from the farms, material use, electricity consumption and fuel use. Secondary data is material production, electricity and fuel generation, transport emissions and waste management processes. Electricity and fuel data are critical when calculating carbon footprint as it is a hotspot. Reported energy use and material input is considerable different between the farmers contributing with data, this can depend on different water conditions (nutrient availability and productivity of mussels) or differences in farming methods. The varying material input might be due to different operating conditions or differences in estimations.

Meyhoff-Fry (2012) further discusses the uncertainties in the cradle to grave scenario. These are: How far and with what mode of transport the mussels are shipped from the farms, as well as the uncertainties in the retail stage, use and end-of-life phases. These phases correspond to over 60% of the emissions, hence, have a great impact on the emission. Both Cajas de Glinwicz (2016) and Ziegler et al (2013) assessed the mode of transport after processing, whether it is by plane or truck, which also has a great impact on the final emissions.

Another type of uncertainty is what is included in the different inventory assessments. Meyhoff-Fry (2012) discussed capital burdens and concluded it to be out of the scope of her assessment. It would however, according to inventory assessments from the farmers, contribute with 16% of the total emission, resulting in ~40 kg CO_2-eq/tonnes product. No other report analysed assessed the capital burdens. Aubin et al., (2018) and Thomas et al. in prep. reports “transport” both with boats and tractors, the other cases reports “fuel use”. There are differences in the values extracted from the database Ecoinvent, whether it is “fuel use” or “transport with tractor” the later, also includes production of the equipment.

Frösell (2019) and Hallberg (2018) both reported that big bags used for transport of mussels after harvest had the individual greatest impact. This is since they are no longer used within the systems resulting in a lifetime of one production cycle. It is unclear, whether they are new when used for shipping or if they are further reused at the processing plant, both assumptions would alter the final impact, but they are out of the scope of this essay.

4.1.1. Carbon sequestration

Carbon sequestration can be seen as an uncertainty as there is no common practice of how it should be included, or if it even should be included. Hence creating a great variation of the result. This is a methodological difference between the studies that was found to be outside the scope of this thesis. Here follows a compilation of what the previous reports have discussed and how they differ.

Meyhoff-Fry (2012) includes the shells of the mussels distributed, the mussels dropped to the ocean floor and the ones that are thinned from the suspended ropes. Further, carbon credits are discussed and difficulties in reaching consensus are assumed.

In Aubin et al. (2018), shells are seen as means of sequestration but not the flesh or respiration. Shells discarded at processing and at household waste are seen as carbon sinks. Of the wooden poles, 50% of the carbon is sequestered from photosynthesis while living and by being rot-proof after their approximately 15 years in the ocean. The sequestration compensates for the emission from on-site transportation, with little or low climate change but it cannot be considered a carbon sink. They further conclude that the carbon cycle in marine ecosystem are complex making it difficult to draw any conclusions.

Ray et al (2018) argue that emissions from shell production should increase the carbon footprint. In shell production, dissolved bicarbonate (HCO_3^-) and calcium (Ca^{2+}) forms calcium carbonate ($CaCO_3$) (equation 1). The CO_2 is either released to the atmosphere or prevent further uptake of atmospheric CO_2 into the water. When recalculating previous LCA's about bivalves the CF increased with 250% The CS was lower than the released CO_2 in respiration in cultured Mediterranean mussels.

$$Ca^{2+} + 2HCO_3^- \leftrightarrow CaCO_3 + CO_2 + H_2O \quad (1)$$

Ray et al (2018) proposes that the shell formation should not be included as a carbon sequestration is inorganic carbonate and not organic carbon. They further argue that the carbon content of the flesh should be included though, as the phytoplankton filtered consist of organic carbon. Aubin et al (2018) argue however that the carbon in the flesh and from respiration is part of a shorter life cycle and should not be included in CS.

Ray et al (2018) further discusses how to negate the CO_2 emissions. With or without carbon sequestered in the shells, the shells should be used as an alternative to products with higher carbon footprint to reduce the emissions. The shells could be used as limestone or as quarried sand in cement (Ray et al., 2018) or as extra structure for roads also proposed by (Aubin et al., 2018). The shells could further be used to restore estuarine reefs for habitats and to provide ecosystem services (Ray et al., 2018).

4.1.2. Harmonization

The choices of harmonization have a great impact on the recalculation. Here follows a discussion of the choices of methodology made for this thesis.

Goal and scope of this thesis

As evident from table 1, a great variety of functional units were assessed in the analysed articles showing the need of a uniform compilation and harmonization before comparing. The system boundaries and the choice of only assessing the emissions were chosen to minimize the variance and to highlight the production. As many of the articles have shown the processing step creates a great variation in the final emissions this was excluded.

Eutrophication potential and carbon footprint were chosen as impact categories due to the relevance for mussel cultivation. In table 1, the impact categories analysed in each case are shown, carbon footprint and eutrophication are the most common. Eutrophication is reduced as nutrients from the water are taken up. The calculated mean impact of emissions of 0,005 kg N-equivalents/tonnes produced or 5 g N-equivalent/tonnes produced is quite low when 1 tonnes of mussels can take up 6,4-10,2 kg of nitrogen (Lindahl et al., 2004). This was excluded from the study as the uptake depends on several factors and the uncertainty was expected to be high. The surrounding environment affects the uptake, nutrient availability and hydrology (Lindahl et al., 2004), at the same time the hydrology set the requirement of the infrastructure, meaning that the impact per the material of the infrastructure affects the emissions, while at the same the environment affects the nutrient uptake. Further investigation about the surroundings, to analyse and distinguishing the importance of the hydrology and the nutrient availability would be needed. Hence, a mean nutrient uptake would not be representative and was therefore excluded in this study.

Carbon footprint is an important and common impact category facilitating the comparison among different assessments and different food stuffs. The acidification potential affects the shell formation of mussels and would be of interest for further investigation.

Recalculation

Thomas (in prep.) includes transport in his assessment, this was included in the fuel and energy-hotspot. However, the transportation by barge includes material used (see appendix II). Hence a more thorough modelling would be desired for further investigation, to separate the transport from the fuel use.

Material used and lifetime

The choice of harmonizing the material used has an impact on the emissions. There might be conscious choices of using one material over another by the farmer due to the environmental impact. It would be of interest to model the different materials to map the differences. The choice of material might depend on requirements on the infrastructure from the surroundings (Thomas 2020). The assumption of using the same lifetime per the material is therefore an uncertainty as the surroundings can cause different strain on the material. More thorough research and data on the lifetime and how much it differs per the different areas would therefore be needed. The lifetime should perhaps not be assessed per material but rather per what it is used for. Hallberg (2018) assessed that “ropes to buoys” by polypropylene had a lifetime of one year, while “ropes to concrete anchors” also made of polypropylene had a proposed lifetime of 15 years. This indicates that the ropes to buoys is changed every production cycle. Perhaps being under bigger strain or of another thickness and not as sturdy. However, not all cases have been as thorough in their inventory data and states what each material is used for. In the assessment of Frösell (2019) big bags are used for several purposes, within the production site the big bags are used “until they break” (Persson 2020). However, when the big bags are used for shipping, they are disposable. Hence, the lifetime of the same material varies within the production. With harmonization of the lifetime this difference is not noted and affects the result.

When recalculating the inventories with harmonized lifetime the result from the data set from Thomas et al. (in prep) declined from 63 kg CO_2/ton to 5 kg CO_2/ton. The recalculated 5 kg CO_2/ton corresponds well to the result from the data set (see table 4). This indicates that the lifetime might already be assessed, further proves that not all assessments are done in the same way. These data came from an unpublished dataset with no reported method description. The harmonization of the lifetime followed the methodology of this thesis, this further shows the need of a more thorough review.

4.2. Comparison with other products

When comparing mussels to other products, both as food and as an ingredient in animal feed, there are many aspects to assess. What is it compared to? What would be used or cultivated instead? What would happen to the areas without the mussels – more eutrophication? What would be eaten instead? One might not exchange beef for mussels as a comparable meal experience even if Cajas de Glinwicz (2016) argues that the nutritional value can be compared. Iribarren et al. (2010) compared three different mussel products *(Mytilus galloprovincialis),* (fresh, canned and boiled-frozen) to chicken and canned tuna. Chicken was chosen as it is a common food to compare with for environmental impact. Tuna was chosen as it would be something to replace with mussels. The comparative LCA used 1 kg of protein as the functional unit and due to the low protein content of mussels, they had a bigger environmental impact than the compared foodstuffs.

Aubin et al (2017) and Meyhoff-Fry (2012) compared mussels to other foodstuffs. Both found that mussels have the lowest environmental impact (per AP, EP and CF) and that beef have the highest. When comparing to other foodstuff, the FU is per ton edible protein. In the comparison, 27% of the mussel is expected to be flesh and 11,9% protein, (Aubin et al., 2018). Due to the low protein content, the energy consumption per the protein content is among the highest. Fish from aquaculture have a very high variability, ranging between 146 000 to 1 584 000 MJ, but otherwise mussels with 225 000 MJ/ ton edible protein is the highest, as compared to beef with 146 000 MJ/ton edible protein or chicken 150 000 MJ ton edible protein.

Meyhoff-Fry (2012) compared the carbon footprint /kg edible product of Scottish mussels and oysters to other foodstuffs and found that mussels had 0,25 kg CO_2-eq/kg and oysters had ~9 kg CO_2-eq/kg edible product as compared to sheep and beef which had ~19. Farmed salmon, British poultry and pork production scored lower than oysters. The authors further state that the sources used for the comparison haven't evaluated the methods used. The protein content in mussels is not assessed as in Iribarren et al (2010) or Aubin (2018).

On site at sea, mussels have a higher environmental impact than salmon, when comparing the FU of 1 kg edible product. This is due to the small volumes produced and the emission from the boats during maintenance and harvest (Ziegler et al 2013). The independence from manufactured feed lowers the environmental impact when looking at the whole production compared to fed aquaculture.

Hilborn et al. (2018) compiled LCAs of animal sourced foods. They grouped the assessed reports into three different groups, livestock, aquaculture and capture fisheries. The assessed impact categories were AP, EP, energy consumption and greenhouse gas emissions (GHGE). The functional unit is per 40 g of protein. The unfed molluscs scored the lowest in all categories, only capture fisheries of small pelagic fish scored lower in energy consumption and GHGE. In the EP, molluscs scored the lowest as they remove nutrients from then environment. Since capture fisheries do not rely on fertilizer, it also scored low. Small fish in dense schools showed to have the lowest impact.

Thrane (2008) looked at fuel use in the Danish fishing fleet and found that fishing of mussels (fished using mussels dredges) showed the lowest fuel consumption among the species included in the study, both relative per caught kg and the total consumption, as low as 0,012 L fuel/kg. The consumption increased when changing the FUs, from kg liveweight to edible product, since considerably more mussels need to be produced to deliver one kg of mussel product due to the low edible yield (24%). However, the fuel use is so low that when changing the FU, the fuel use is still lower compared to other seafood products. These numbers can be compared to 6 L for Norwegian lobster and 0,06L for mackerel.

Due to the nutritional value and the low environmental impact during cultivation, mussels could be included into several products. It could be included as a meal as feed additives but also for human consumption (Musselfeed 2016). Mussel sausage for example showed to have a five times lower impact than meat-based sausages (Vinnova 2017). A high potential for further development of new products, pâtés and cold cut sausages for sandwiches was hypothesized in that study.

4.3. Production

Mussels are produced without input of feed or other additives. Hence, the two main hotspots are material and fuel use which become the major inputs.

The reports mention a relatively high loss from the harvested biomass, 20-30% (Aubin et al., 2018, Lindahl et al., 2004). Mussels are discarded for their small size or broken shells. In Aubin et al. (2018) the waste went to tractor-roads, this stabilizes the roads and keeps the predators away from the cultivation area. The low edible yield (24%) further increases the waste. When assessing per edible product, Winther et al (2009), concluded that for 1 kg mussels transported to Paris from Norway, 4,2 kg were washed and sorted. This means that only 24% of the mussels cultivated are used. The re-seeding technique assessed by Frösell (2019) allows the undersized mussels to be re-seeded for further growth instead of becoming waste. Modern grading equipment minimizes the risk of crushing the mussels, further lowering the amount of waste (Frösell 2019).

Different areas provide different productivity because of the amount of plankton but also because of hydrology and currents (Lindahl et al., 2004). Hydrology also causes a different strain on the infrastructure (Thomas 2020). The two farms assessed by Thomas et al., (in prep), one on the west coast and one on the east coast have similar emissions calculated per produced tonnes (see table 2), however, there is a great difference in productivity. The rigs on the west coast are more robust as they must withstand harsher conditions hence a higher impact but also a higher yield due to the more advantageous higher salinity. The less robust rigs at the east coast have a lower impact and but also a lower yield. In the Baltic sea, the rigs must be able to withstand ice in a greater extent than in other areas, this poses difficulties for the rigs and placement is of importance (ERAC 2020). The productivity in the Baltic sea is doubted but trials with new types of culture ropes raised hopes that productivity can be increased enough to make farms profitable (Thomas 2020).

Two risks and obstacles mussel farmers face are predation and legislation (Person 2020). Legislation might hinder the entrepreneurship and the profitability. The decrease in production in Europe can be connected to limitations due to legislation (Wijsman et al. 2019), especially for bottom production in the Netherlands. There is an ongoing discussion whether the disposal of mussels from Buchot culture to stabilize tractor roads is an approved method or not, due to smell nuisance. In Sweden crushed mussels and shells from mussel farms were earlier used as fertilizer on nearby fields, this is not allowed anymore (Persson 2020), due to legislation related to animal by-products.

Oyster aquaculture in the Mediterranean have crashed twice in the 1970's. In 1971-1973 there was a depletion of oysters in Portugal. In 1979 the parasite *Bonamia Ostreae* (Wijsmann et al., 2019). The outbreaks caused mortality and disturbed the production. Proving that bivalve production is sensitive to external factors.

4.3.1. Risks of consumption

There are some risks connected to consumption of mussels that are important to address. Food poisoning from viruses and bacteria, as well as risk of intake of algal or environmental toxins and the risk of consumption of heavy metals. Due to filtrating the particles are concentrated within the mussel's hepatopancreas, (an organ comparable to both the liver and pancreas in mammals). When consuming mussels, the whole animal is consumed, including the hepatopancreas as compared to other animals where the intestines are removed (Beckman Sundh and Toljander 2017). The most common cause of food poisoning from mussels is norovirus, it stands for 84% of the outbreaks globally (Rosengren 2017) and only 10-100 virus particles can cause disease (Beckman Sundh and Toljander 2017). In warmer oceans different strains of *Vibrio* can cause food poisoning associated with consumption of bivalves (Beckman Sundh and Toljander 2017).

Algal toxins are secondary metabolites originating from phytoplankton. The toxicity can vary between different occasions and geographical areas (Beckman Sundh and Toljander 2017). The mussels are not affected by the toxin but become a vector (Rosengren 2017).

There are two main toxins responsible for most of the food poisoning. Diarrhetic shellfish toxin (DST) and paralytic shellfish toxin (PST). DST causes diarrhoea, nausea, vomiting and stomach pain, the symptoms can arise within half an hour or in a couple of hours. The symptoms are often harmless and pass within a few days and do not leave any permanent damages. PST is a neurotoxin where the symptoms can arise within minutes after consumption. The symptoms vary between a tingling feeling in the face to more severe symptoms such as muscle weakness and numbness in arms and legs. It can also cause stomach flu, problems with coordination, confusion and fatigue as well as a feeling of absence. At severe poisoning, it can cause muscle paralysation and respiratory problems (Rosengren 2017). PST have never caused an outbreak in Sweden but have been found in production areas. The Swedish food agency controls the production areas weekly in order to detect high levels of algal toxin or bacteria. Exceeded limits force the farm to postpone the harvest (Rosengren 2017).

Cooking does not inactive the toxins, DST is fat soluble and concentrates during cooking, also freezing does not affect DST. PST is water soluble and reduces in the cooked as compared to fresh mussels as the toxin leaches into the cooking-water (Rosengren 2017).

4.3.2. Economic aspects

The global annual cultivation of bivalves was worth 20,6 billion US$ in 2019 (Wijsmann et al., 2019), the market value was 23 billion US$. However, the total economic value can be higher due to secondary products and services, including transport, manufacture and retail of processed products. FAO (2014) concludes that one employee equates the production of 20 tonnes of mussels, with a potential of increased production of 190 000 tonnes this would equal 9500 new jobs. One blue mussel farm with 1,2 million dollars in sales may generate a total of 6,49 million dollars in total economic effects when assessing both the farm and restaurants (Cajas de Glinwicz 2016).

In the US in 2016, a kg of beef costed $4,21, a kg salmon fillet costed $5,25 and 1 kg of mussels costed $5,48 (Cajas de Glinwicz 2016). Comparing this to Swedish prices in 2020 a package of salmon costs 125 SEK/300 g (Mathem.se 2020a) or frozen 199,90-223,13 SEK/kg, and beef 329 SEK/kg (Ica.se 2020), as to compare with a net of mussels that costs 65 SEK/kg (Mathem.se 2020b). With an edible yield of 24% (Winther et al., 2009), 1 kg of mussels gives a portion of 240g. The price per edible portion of mussels is then 270,8 SEK/kg.

Besides the economic value of food, the ecosystem services provided by shellfish aquaculture also generates economic value. A company can buy “nutrient credits”, a “right” to emit a certain amount of nutrients and a mussel farmer removes that amount (Lindahl et al., 2004). This is an example to increase the profitability of the cultivation. The total global economic value of the ecosystem services is 30,39 billion USD (US $ per 2017 value) (van der Schatte Olivier et al., 2018). Food stands for 23,92 billion USD and nutrient remediation for 1,2 billion USD and shells used as aggregates worth 5,27 billion USD. There is however a great uncertainty of how to value the regulating services of nutrient removal (van der Schatte Olivier et al., 2018), also reconnecting to the ongoing discussion about carbon sequestration and nutrient uptake. Phosphorus removal corresponds to US$ 13 118-58,561 /tonnes removed and nitrogen to US$ 8 996 – 31 050/tonnes removed (van der Schatte Olivier et al., 2018).

Another way of increasing the profitability as well as to increase innovation and entrepreneurship would be to sell the “know-how” of mussel farming (Persson 2020), solutions and installations, to new or established farmers that want to change their cultivation.

4.4. Recommendations

The recommendations mentioned are divided per production and per further investigation.

4.4.1. Production

Even though mussel cultivation is a low-impact aquaculture, more can be done to further reduce the impact (Aubin et al., 2018). Making the production more energy efficient is seen as the greatest potential to reduce the environmental impact (Meyhoff-Fry 2012, Aubin et al., 2018). Using boats for multiple tasks or farmers sharing vessels would make it more efficient. Use of renewable forms of electricity is another proposal for reducing the emissions. Assessing the cumulative energy demand (CED) would make the energy use more visible and can enhance the strengths and weaknesses of the production. The CED shows the renewable and the fossil fuels (Thomas 2020). Prolonging the lifetime of materials used or choosing low-intensive materials are other examples of reducing the emissions which stand for approximately 40% of the cradle to gate footprint and 20% of the cradle to grave footprint (Meyhoff-Fry 2012). More energy efficient boats, further investigation about waste and waste treatment, and more documentation from farms are recommended (Aubin et al., 2018). On the farm which Frösell (2019) assessed, barges are used at the farming site and small boats are used to get to and from the site, rather than using big boats for maintenance.

In general, 1/3 of the mussels produced in traditional long-line mussel farming become waste (Lindahl et al., 2004). This is either because of their size or because of broken shells. In Norway 7,3 kg of unsorted mussels need to be harvested, to have 1 kg of edible mussel in (Winther et al., 2009). This loss generates a higher environmental impact per produced tonne. The loss is also a cost for the farmer, waste which must be handled. For example, with the new legislation the waste can no longer be used as a fertilizer (Aubin et al., 2017, Persson 2020). New production methods could further reduce the loss, for example better control of the density and growth with newly designed ropes or through the re-seeding technique (Frösell, 2019). In addition, the re-seeding of the too small mussels lowers the amount that would be disposed considerably. This further lowers the amount of waste and the cost of disposing the mussels. Optimizing the production so even fewer mussels will be crushed and disposed of in the future is of importance (Persson 2020).

Tube-dwelling polychaetes is a worm that lives on the shells of the mussels producing calcinate tubes, which makes them less appetizing and lowers their market value. Today, there is no further market for these mussels. There is no processing plant of mussels in Sweden that could boil them or further process them. The closest processing plant for boiling is in Denmark but, the mussels were too big and did not make an appetizing product "only became mush". Perhaps a processing plant in Sweden that accommodate the bigger mussels. Or to feed even though the profitability is lower.

The discarded mussels, whether because of the wrong size or because of fouling, could be used for restoring mussel banks, which are important ecosystems as nurseries for several species increasing the biological diversity.

4.4.2. Further investigation

In this thesis the system boundaries were "cradle to gate". It would however be of interest to analyse mussel's total environmental impact throughout the whole lifetime through a "cradle to grave" scenario including consumption aspects. This was however outside of the scope of this essay.

Furthermore, more thorough investigation and modelling of blue mussel LCAs as well as more data with the goal of better distinguishing differences per material used as well as to separate "transport" and "fuel use" are needed.

A similar comparison of methods with other bivalves or even other food stuffs would be of interest.

5. Conclusions

The objectives of this study were to compile and compare existing LCAs on blue mussel production through a literature review, and through a recalculation of the inventory assessments to obtain comparable LCA results. The ultimate goal was to provide a current report of what data exists and what conclusions that can be drawn about blue mussel production. As mussels are gown without feed the material and energy and fuel use are the main inputs. A more thorough modelling could further highlight differences in inputs of production in further investigation

An important observation was that there is a high factor of variance when farmers reported data and that a more thorough investigation is needed for more solid conclusions. The samples analysed is small and may not be representative for the whole blue mussel industry. It is however a current report of existing LCAs.

The harmonization of the lifetime per material and the decisions regarding the material use affects the environmental impact.

Blue mussels have a relatively low environmental impact with a mean carbon footprint of 0,95 kg CO_2-eq./kg and a eutrophication potential of 5 mg N-equivalents/kg produced mussels with shells per the emissions. Biologically, a negative eutrophication potential is expected due to the removal of nutrients at harvest. The mitigation of eutrophication is an important aspect of bivalve production and should not be ignored, but rather high-lighted.

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Appendix I

Presentation of the evaluated cases

Here follows background information about the assessed cases.

Frösell 2019 (Bachelor's thesis – Swedish university of agricultural sciences

The farm analysed is located on the Swedish west coast and uses a suspended long line production system. To control the density and the growth of the mussels a method of harvesting and reattaching is performed, this is both energy and material consuming. The reseeding technique minimizes the loss and waste due to too small mussels.

The same farm was visited on the 27 of April 2020 for a study visit. Katrin Persson, the CEO, showed the production barges and gave valuable insight to the mussel production and discussion of this thesis.

Hallberg 2018 (Bachelor's thesis – Gothenburg University)

Assesses the CF and the EP for different scenarios for a mussel farm in Denmark with a suspended production system Different FUs were assessed; live weight with different system boundaries, cradle to gate or cradle to grave and per edible weight. When including processing steps, the value increased, processing and packaging contribute with 79% while farming and transportation contributes with 10% each.

Aubin et al 2018

Four bouchot farms close to St Michael were assessed. Farms further out in the English Channel had better access to a current which increased the production and yield, other farms were closer to the processing plant, thus, having lower environmental impact from transports. The yield influences the environmental impact. In this study yield affects the carbon sequestration and the general impact as the FU is per ton "ready to cook mussels". A "ready to cook mussel" is a mussel from which the byssus has been removed but with the shells remaining. The byssus are fibers produced by the mussels for anchorage (Cultimer.com 2020). The system boundaries were, from spat collection, including the on-growing phase until the mussels leave the processing plant, distribution and consumption stages were excluded. However, management of household waste was included to consider the shells.

Meyhoff-Fry 2012

This study was analysing the carbon footprint from suspended longline mussel cultivation in Scotland. The study includes data from 23% of the Scottish mussel farmers. The study assesses different scenarios, cradle to gate and cradle to grave as well as with and without depuration and carbon sequestration, a total of eight scenarios. The following system boundaries are used: spat collection, thinning, harvest, grading, (depuration when required) and packing. The cradle to grave perspective further includes: transport & reprocessing, distribution & retail and use & disposal. Capital equipment in the form of vessels and machinery, and staff commuting were excluded from the study. The FU is per tonne product and per 500 g serving when comparing with other food stuffs.

Thomas et al., in prep.

The un-published data set analyses two Swedish farms, one on the west and one on east coast. The east coast of Sweden has more brackish water (0,6 ppm) than the west coast (1,5-3,4 ppm) and the mussels are often smaller and not fit for human consumption but used to produce biogas or being explored as a mean to mitigate the eutrophication or in animal feed (ERAC 2020, Havet.nu 2020, Thomas 2020). This study also focusses on the recovery of phosphorus from marine environments, to close the marine-land loop and contribute to phosphorus security.

Winther et al. 2009

In a case study from Norway, data from three different farms have been weighted together. They conclude that the data is not be representative for the Norwegian mussel sector due to the small selection, and as there is a variation between different farms.

Henriksson & Ståhle 2019 (Master's thesis – Linköping University)

This study assesses a mussel farm in the Baltic sea. The farm is in a trial phase and the inventory data had been assessed by one of the farmers and not measured exactly.

In the Baltic sea it takes two years for the mussels to grow and a lifetime of the materials used of ten years was assumed, the amount of material has been divided with a factor of five. This have been taken into consideration for the recalculation. Three different scenarios were assessed, worst, modest and best, for when the farm is developed to a commercial scale and no longer in a pilot phase. The result is compared to the worst case as it corresponds to the inventory assessment. Future development is assumed to lower the emissions due to change of fuel, from petrol to electricity. The material used per tonnes of Blue mussels is assumed to be similar between the different scenarios.

Appendix II

List over materials, fuels and transports used for the calculations, from the data base EcoInvent. Values in kg CO2-eq. or kg N-eq./kg material used. Density used for calculations for cotton and concrete.

GWP – global warming potential, EP – Eutrophication potential.
Table 1.

		GWP	EP	Lifetime (mean)
		(kg CO2-eq/kg)	(kg N-eq/kg)	Years
MATERIALS	Steel, low-alloyed, hot rolled {GLO}| market for | APOS, S	2,13	5,63E-05	22,5
	Polypropylene, granulate {GLO}| market for | APOS, S	2,18	1,08E-05	20,83
	Polyethylene, high density, granulate {GLO}| market for | APOS, U	2,16	2,98 E-06	16,25
	Injection moulding {GLO}| market for | APOS, S	1,35	4,79E-05	20
Density: 1875 kg/m3	Concrete block {GLO}| market for | APOS, S	0,0911	1,53E-06	25
Density: 40 kg/m3	Textile knit cotton, {GLO} | market for | APOS, S	21,8	4,00E-03	1
	Polyinvylchloride, at regional storage/RER S	2,05	4,43E-05	20
	Polyueruthan, flexible foam at plant /RER S	5,19	1,26E-03	20
	Polypropylene, granulate {GLO}| market for | APOS, S + Injection moulding {GLO}| market for | APOS, S	3,53	5,87E-05	22,5
FUELS	Petrol, unleaded, burned in machinery {GLO}| market for petrol, unleaded, burned in machinery | APOS, S	0,0865	2,21E-07	

	Diesel, low-sulfur {RER}| market group for | APOS, S	0,546	8,95E-06	
	Heavy fuel oil {Europe without Switzerland}| market for | APOS, S	0,469	7,24E-06	
	Electricity, medium voltage production CENTREL, at grid/CENTREL S	0,263	1,89E-05	
TRANSPORTS	Transport, tractor and trailer, agricultural (RoW) processing APOS, S	0,375	7,71E-06	
	Operation, barge/RER, S (bara frakten)	0,0356	1,04E-07	
	Transport, barge/RER S (includes production, maintenance and port	0,0467	4,67E-07	

Conversion rates for fuel

Table 2. The conversion rate between L and kWh.

Reference: miljofordon.se/ekonomi/drivmedelskalkyl

Fuel	**L**	**Kwh**
Gasoline	1	9
Diesel	1	10
Electricity	1	1

Table 3. Conversion MwH to MJ and MwH to kWH

1 Mwh	3600	MJ
1 Mwh	1000	kwh

Table 4. Density of petrol, diesel

Density		Unit	Reference
Diesel	0,832	kg/L	quora.com/How-heavy-is-a-liter-of-diesel-in-kilogram (accessed 2020-05-24)
Motor oil	0,85	kg/L	quora.com/How-many-kilogram-in-1-liter-of-engine-oil? (accessed 2020-05-24)

Appendix III

Popular scientific summary

Mussels are not only tasty they are also healthy and good for the environment! The goal of this thesis was to evaluate the emissions of the production of blue mussels.

With a growing world population there is an increased demand of sustainable and healthy food stuffs. There is not much more land to farm on whether for food or for feed for livestock. Aquaculture has increased more than any other production method, however there is often still a need for feed. Feed is both a cost and a source of waste, and it either need land to farm or wild fish for fish meal and oil.

Blue mussels are a species that grow without input of feed, fertilizers or antibiotics. They are filter feeding organisms consuming plankton and other particles. During harvest, nutrients are removed from the ocean, reducing the eutrophication. Blue mussels are tolerant, enabling a wide distribution in different ecosystems. Managing both differences in salinity, from high salinity to brackish water and through a high variance in temperature. Besides providing food and feed so called ecosystem services are provided during cultivation. For example, the filtrating of plankton improves water quality and allows more light to penetrate the water column, resulting in better growth for algae on the sea floor. The algae then produce oxygen preventing the anoxic and dead bottoms. The nutrients removed during filtering can be traded as nutrient credits, where a company pays to be allowed to emit a certain amount which the mussel producer then removes with the mussels.

There are also risks connected to mussel consumption, food poisoning through virus and bacteria or algal toxins and intake of heavy metals. Virus and bacteria become inactivated during heating, the algal toxins are often heat stable and remain toxic after cooking. Mussels can only be sold if they are controlled by the national food agency.

There are mainly three different cultivation methods, bottom culture, suspended culture and Bouchot culture. In Bouchot, wooden poles are fixated on the shore onto which nets or ropes with mussels are attached. In bottom culture, young mussels are collected from the wild and placed onto plots sheltered from predators. In suspended culture, ropes are suspended from either rafts or lines, this technique is more common where the sea is too deep for bottom or bouchot culture.

Life cycle assessments, LCA, is a standardised method of calculating environmental impact. It can be used for comparison between different products as well as used as a marketing technique when communicating the result.

The goal of this thesis was to compile different cases of mussel cultivation, to be able to draw conclusions about the production. In this thesis, six reports and one data set were reviewed, and the environmental impact was recalculated. Using the same material and lifetime in the recalculation reduced the variation and highlighted the differences in the production.

Mussels had a mean of 0,95 kg CO_2-equivalents/kg and 5 mg N-equivalents/kg per the emissions but a negative eutrophication potential when regarding the nutrient uptake. The nutrient uptake depends on several factors and would be difficult to model and assess and was therefore excluded from this study. Hotspots identified was production of material followed by energy and fuel use. As mussels are grown without input of feed and other additives, material and fuel are the two main inputs. Even though mussels have a low environmental impact, using more energy efficient boats or farmers sharing vessels could further reduce the emissions. Mussel are nutritional and sustainable, making it an interesting ingredient in new products. Both as feed for animals and perhaps in a sausage.

As a conclusion, eat more mussels!