Life cycle assessment (LCA) of oyster farming in Washington State

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Abstract

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Oysters are a culturally and economically valuable source of food and often promoted as an environmentally sustainable food choice. Life-cycle assessment (LCA) provides a standardized means of assessing the environmental costs of a product but has not previously been applied to oyster production. This thesis develops and applies an LCA for a production system in the Pacific North West (PNW), where oyster farming represents a major part of aquaculture production. Contemporary PNW oyster production typically consists of a hatchery, Floating Upweller System (FLUPSY), grow-out, and processing subsystems. LCA was used to quantify a suite of global scale resource depletion and environmental impacts of single-seed oyster aquaculture (individually grown instead of cultched), from cradle to retail-gate, using five different impacts categories: global warming potential (GWP), ozone depletion potential (ODP), marine eutrophication potential (MEP), human toxicity potential (HTP), and cumulative energy demand (CED). Two varieties of Pacific oysters (*Crassostrea gigas*) were analyzed using a functional unit (FU) of one dozen live oysters on the half shell: beach-grown oysters (trade name Classic Pacifics) and tide-tumbled oysters (trade name Shigokus). Results show electricity and fuel as the dominant contributors to impacts, with infrastructure, water use, and chemicals as minimal contributors. The contribution of each subsystem to total resource demand varied with each impact category. Production of Shigokus had slightly higher impacts overall, due to higher material use during the grow-out phase compared to Classic Pacifics, even though they have a higher survival rate. As a non-intensive and non-fed system, oyster aquaculture overall had low values per each impact category, confirming claims that they are a low environmental impact food choice.

Acknowledgements

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Glossary of Key Terms

LCA – life cycle assessment

Impact Category – class representing environmental issues of concern to which life cycle inventory analysis results may be assigned[1]

Functional Unit – quantified performance of a product system for use as reference unit[1]

Classic Pacifics – beach-grown variety of Pacific oysters (*Crassostrea gigas*)

Shigokus – tide-tumbled variety of Pacific oysters (*Crassostrea gigas*)

Hatchery – initial stage of oyster aquaculture involving algal production and resulting in 2mm oyster seed production

FLUPSY – (Floating Upweller System) nursery stage of oyster aquaculture resulting in 6-12 mm oyster seed production

Grow-Out – phase in oyster aquaculture in which oysters are placed on beaches using various methods to grow oysters to harvestable size

Processing – final phase of oyster aquaculture in which oysters are sorted and packaged for distribution to market

GWP – Global Warming Potential

ODP – Ozone Depletion Potential

MEP – Marine Eutrophication Potential

HTP – Human Toxicity Potential

CED – Cumulative Energy Demand

CHAPTER ONE

Defining Sustainability with Life Cycle Assessment

What do we consider sustainable seafood?

The term 'sustainability' has long been evolving in both its definition and its application.[2-4] At the forefront of this movement towards better environmental stewardship and conservation of resources for future generations, is concern over what food we eat.[5-6] With growth in food production comes increased environmental impacts. This has been well documented in agriculture and livestock farming, with current practices raising concerns over greenhouse gas (GHG) emissions, land and water use, and the release of toxins into the environment.[7-8]

Every food production system has an environmental cost, and fishing and aquaculture are no exception, with problems such as habitat destruction for fish farming or overexploitation of natural stocks.[9-11] Seafood has long been a valuable and nutritional source of food for many people across the world, with global per capita human consumption steadily rising.[12-14] Much of this increase in demand is due to greater affluence, stronger marketing and production, and general human population growth.[12, 15] To add to this, many people are showing an increased preference for seemingly more sustainable products,[16-17] which has led to sustainable certification programs in fisheries and aquaculture.[18,15,19] This is in response to concerns such as overfishing, pollution, climate change, health hazards, and threats to human well-being.[18]

Recently, many wild-caught and farmed seafood products have gained recognition as being sustainably-sourced.[20] This spurs critical thought about what can be classified as "sustainable". There already exist various forms of eco-labeling for consumers to use as guidance in terms of what seafood they should and should not purchase.[19] Consumer awareness programs include "fish lists" such as The Monterey Bay Aquarium's Seafood Watch Program in which seafood sources are listed and categorized as "best choice", "good alternative", or "avoid" options based on the program's sets of 'Guiding Principles' for both aquaculture and fisheries.[21-22] Seafood products are binned according to scores automatically calculated within the Seafood Watch

Assessment Tool and criteria supplied from expert researchers, industry personnel, and policymakers.[23] Other similar lists include Blue Ocean Institute's "Guide to Ocean Friendly Seafood" and the Environmental Defense Fund's Seafood Selector.[24-25] In contrast to these sustainable seafood consumer awareness initiatives, are seafood eco-labeling programs. Amongst these, perhaps the most well-known and respected is the Marine Stewardship Council (MSC) which certifies wild stocks in accordance with independent certifiers that follow their 'Principles and Criteria for Sustainable Fishing'.[14,26] Following suit is the newly developed Aquaculture Stewardship Council (ASC), which aims to do the same for farmed seafood by setting standards for certification.[27]

A number of issues associated with seafood production are often overlooked in many of these current consumer-facing sustainability assessment or recommendation processes.[19-20] These methods often focus on stock status, and harvesting issues such as bycatch. They fail to include the broader environmental impacts inherent in any food production system, including concerns over greenhouse gas emissions or potential for pollution.[16,20,19] For instance, the 'Guiding Principles' of the Monterey Bay Aquarium's Seafood Watch program (which determine the sustainability of seafood products) include the following considerations: habitat protection, sustainable feed ingredients, dependence on wild stocks, the introduction of non-native species, and impacts and emissions of the practice itself.[21] This leaves questions such as the following unaddressed: how much fuel is burned by fishing vessels, or what materials and resources are used in processing, packaging and transporting a frozen fillet? Thus, the environmentally conscious consumer, organization, or policy-maker is left with an incomplete understanding of the extent of the environmental demands associated with different food choices.

Life Cycle Assessment (LCA)

This is where life cycle assessment (LCA) comes into play. LCA is a tool that can be used to help answer many questions that are traditionally not considered in seafood sustainability schemes. LCA practitioners are able to calculate the environmental impacts of a given` production system into comparable and quantified units.[28,17] This methodology takes a "cradle-to-grave" approach, beginning with the assemblage of raw materials and resources used in production and ending with disposal, thus providing a holistic analysis of a number of environmental impacts of products (in this case, seafood products).[1,29,28,30] For example, one LCA study followed the production of one ton of live lobster starting with the building of traps and the use of bait, continuing through the supply chain, and ending with lobster on a dinner plate – while simultaneously including all of the prior occurring activities that provide raw material inputs to all of these activities.[31] Life cycle assessment describes a summation of events in a process.[32] As Ziegler et al. (2016) mentioned "not even certification, which assesses products, takes a product perspective"; i.e. programs like the Marine Stewardship Council do not consider all the background processes that go into producing seafood.[20]

The trend in current assessment methods is to aim for a more inclusive perspective on sustainability.[32] Yet, there remains a need for accurate, broad, and comparable information on seafood products to enable consumers to make informed decisions.[17,33] For instance, concerns in aquaculture include high feed loads leading to eutrophication and introduction of parasites and chemicals.[34-35] There are countless ways in which resource depletion and/or environmental impacts arise, especially related to: energy use, vessel construction and maintenance, feed or bait acquisition, and/or transportation of final products. Life cycle assessment can quantitatively account for all of these.[35]

LCA is well suited to help us understand environmental impacts that are not assessed in current fisheries management or certification standards, including greenhouse gas emissions, toxic emissions, land use, and the depletion of abiotic resources.[20] LCA is designed to allow analysts to calculate the effects of seafood production related to these different environmental concerns (also known as 'impact categories'). Such impact categories can include the potential for eutrophication, acidification, or the release of chemicals and toxins into the environment from a given production system. GHG emissions is the environmental impact most commonly assessed by LCA practitioners.[28]

One must also take into consideration that seafood is not produced exactly the same way even within the same type of sector. For example, in aquaculture alone there are more than twohundred twenty species produced either via monoculture or polyculture; subsistence or large-scale industrial production; with different production settings, types of gear, energy sources, and so on.[19-20] Life cycle assessment can be used to understand the implications of this variation in production and resource use, which are integral to the framework of LCA, hence its flexibility in application.[19] Depending on the practitioner's construction of the LCA model, results can be used to determine which sub-processes in a system have the highest impacts – information that is useful to producers wishing to improve the sustainability of their products and/or reduce their input costs.[17] While LCA itself is not considered an eco-label, it can provide a standardized system of data that can be used as criteria for eco-labeling schemes, promoting transparency for suppliers and consumers.[17]

Although the LCA method has many capabilities and shows promising benefits, it does have its drawbacks as a standardized methodology that is used to make comparisons across production systems. While all LCAs share a common standard and core elements, not all follow the same format. Some studies may use different 'functional units' (the basis of analysis used in a given study) for the same species of fish, or they may define systems boundaries differently. For example, some analyses include processes in the production system, such as waste disposal, that go beyond those in other studies. Furthermore, not all LCAs look at the same impact categories. These sometimes subtle differences in LCA practice can, in some instances, make it very difficult, if not impossible to directly compare research outcomes. For some, this may be seen as problematic in that it then makes it difficult to confidently make direct comparisons between results of different studies.[20] To illustrate, suppose you were interested in looking at the environmental impacts of different methods of fishing tuna. One hypothetical study looked at the global warming, acidification, and ozone depletion potentials of purse-seining, transporting and processing of 1kg of canned tuna and another looked at the global warming and marine toxicity potential, and the biotic and abiotic resource use of trolling 1kg of fresh tuna from capture all the way to waste disposal. It would thus be challenging to make legitimate comparisons of the environmental impacts of purse-seining versus trolling for tuna since the studies do not have the same life cycle stages and are not comparing the same product form.[36]

However, if LCA practitioners conduct their analysis with enough detail and separation of subsystems within the process, then it is possible for others to draw careful comparisons via re-analysis. This should not be seen as a failure of the method but as a mis-alignment of primary analysts' specific research objectives and those of secondary data compilers. One of the benefits of life cycle assessment is its flexibility in application and ability to quantify impacts and resource use across a wide range of production systems. Comparison between industries is a potential added advantage of LCA, yet this is not the purpose of any original, or attributional, study.

Knowing where the food we eat comes from, how it was produced, and how the wide range of inputs to these activities contribute to impacts of concern, can, in theory, give retail markets, and policy makers the power to promote sustainable options, paralleling consumer interests.[37] With regards to choosing a protein source, most people in the U.S. are given myriad choices of farmed meat (beef, chicken, and pork) or seafood (fisheries and aquaculture products). All production processes have impacts – nonetheless, they are not equal in magnitude or breadth. Improving the accuracy and transparency of the ecological footprints of these different food systems can facilitate consumer decisions.

Why is it important to perform an LCA of oyster farming?

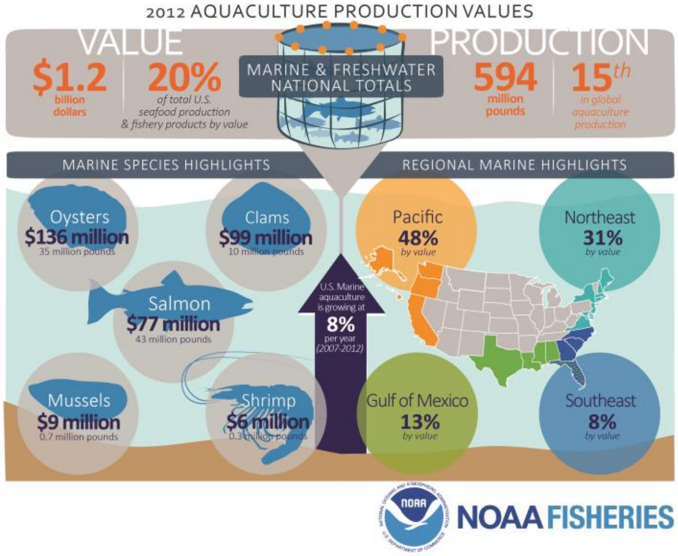
The expansion of bivalve aquaculture

Globally, aquaculture is the fastest growing food production sector,[38,17] with growth rates at nearly 8% per year from 1990 to 2010 - exceeding those of all other food sectors.[39] Aquaculture is an extremely valuable food production system necessary to supply food and nutritional security to a growing world population.[39,13,40] Current estimates show aquaculture supplying the world with half of its seafood demand.[12] Aquaculture is especially important considering depleted capture fish stocks[34-35] and the limited room for capture fisheries landings to expand even under enlightened robust management.[41] Yet, this growth in aquaculture comes with rising environmental costs and implications.[42]

Marine aquaculture, or ‘mariculture’, is prevalent in the United States and overall annual growth rates from 2007-2012 mirror the global rate.[43] U.S. production is dominated by salmon, oysters, clams, mussels, and shrimp, as seen in Figure 1.[43] The proportion of species farmed varies dramatically by region, however.[44] This is most clearly seen in shellfish aquaculture in the Pacific Northwest. The Pacific coast is responsible for producing 40% of national totals for shellfish.[44] This volume is largely due to farmed bivalves (clams, oysters, and mussels).[44] Globally, bivalve aquaculture is a major industry, with steady increases over the last few decades; from 1995 to 2005, production rose from 7.1 million MT to 11.9 million MT of bivalves harvested in various forms.[45]

Washington State has a long history of shellfish farming along its coastline,[46] and leads the country in bivalve farming production.[47] Direct sales of shellfish in Washington State are estimated to be $150 million dollars annually at farm-gate.[47] When taking into account the contribution to the state’s economy, the industry generates substantial amounts of revenue for the state and supports thousands of jobs. As of 2012, NOAA reported that over 3,200 people were employed by the shellfish industry in the Pacific Northwest, and post-production contributed about $270 million to the state’s economy.[48] A Northern Economics Report (2013) states that $1.82 of economic activity is created in Washington State with every dollar spent in the shellfish aquaculture industry.[49]

Figure 1. U.S. Aquaculture Statistics, 2012.[44]



Importance of oysters regionally and globally

Oysters make up a notable proportion of aquaculture products worldwide, most notably the Pacific oyster (*Crassostrea gigas*).[50] As of 2013, the species is responsible for 38% of all shellfish produced in terms of both value and quantity in Washington State.[47] The United States is one of the leading producers of the Pacific oyster – as of 2015 it was the fourth largest producer of live (or cupped) Pacific oysters in the world.[51] Other countries or regions with high production include Chile, China, Japan, Australia, the South Pacific Islands, Morocco, Namibia, the Philippines, Norway, the UK, Spain, the Caribbean, Israel, and Ukraine, among others.[52] This illustrates the global distribution and significance of oyster farming. Global production of live Pacific oysters was estimated at 583,464 tonnes as of 2015.[51] In the United States, oysters bring in the highest revenue of any farmed species ($136 million dollars per year) and are second only to salmon in terms of volume production (35.5 million pounds versus 43 million).[43] As of 2013, the species is responsible for 38% of all shellfish produced in terms of both value and quantity in Washington State.[47]

Aquaculture often gets a bad reputation due to concerns over issues such as high feed inputs causing eutrophication, high loads of fish waste reducing water quality, the spread of disease, and the possibility for escaped individuals to interbreed with wild native species.[13,34] However, oyster aquaculture seems to be an exception to many of these worries. Since oysters and other bivalves require no additional feed inputs, but instead naturally filter feed plankton from their environment, they actually reduce eutrophication potential and increase water quality.[32,35,53-55]

There are notable wider public goods benefits that come from supporting oyster aquaculture. Oysters are culturally important to tribes, family operators, and seafood enthusiasts in the Pacific Northwest. They contain vitamins and minerals that are essential in a healthy diet.[56] Oysters are a good source of iron and zinc[56-57] and contain more than ten times the recommended daily allowance for vitamin B12[58]. Furthermore, Nettleton & Exler (1992) found no significant difference in nutrient content between wild and cultivated oysters – the same could not be said for finfish, which showed higher fat content in farmed varieties. Since these animals are filter feeders and clean water is critical to safe raw consumption, the existence of an oyster industry provides incentives to keep coastlines free of pollutants and raise water quality standards.[38] This is especially important since events such as harmful algal blooms can cause illnesses such as paralytic shellfish poisoning, hence, constant monitoring of water conditions is critical for a successful industry.[59-60]

Lack of data on oysters & bivalve aquaculture

Life cycle assessment is being increasingly applied as a method of quantifying the resource depletion and environmental impacts of various food systems, and in the last decade, this has expanded to include seafood production.[20,17,33,35] Yet, bivalve farming systems in particular (oysters, mussels, clams) have been largely underrepresented in such studies. Parker (2012) reviewed seafood LCA studies conducted prior to 2012 and found that most of the focus within seafood had been on trout and salmon species, and noted the need for further study on the aquaculture of non-salmonids. The review found that among life cycle assessments of aquaculture species, salmonids make up 70% of studies published as of 2012, with mollusks accounting for only 5%.[36] The numbers get even smaller when it comes to bivalves.

There is one LCA analysis of mussel farming in Spain with four case studies within that publication,[61-64] and one on oyster culture in Brazil looking at the recycling of shells.[50] Carbon footprint and energy use were calculated in a case study of a small mussel farm in Norway; their results for mussels were significantly lower than the footprint of the farmed salmon they also assessed.[65] Mussels and oysters were also included in a carbon footprint analysis in Scotland. This study only looked at the greenhouse gas emissions of farming oysters and was not a full LCA, although the results showed a relatively high value in contrast to the previously mentioned study, as a result of intensive farm operations.[66]

The lack of LCA data on bivalves is unrepresentative of their importance as a food source and their contribution to economic and cultural sectors. This is especially true for highly sought after species such as oysters. Given the enormous importance of oyster culture both regionally and globally, this lack of robust understanding of the quantified environmental impacts of oysters farming is problematic.

Research goals & questions

The purpose of this life cycle assessment is to quantify production impacts of Pacific oyster aquaculture characteristic of coastal Washington State using a suite of established and globally relevant impact categories. This analysis is specific to the farming of oysters destined for raw consumption (i.e. live oysters on the half-shell). Specific research questions are as follows:

1) **How can standard LCA methodologies be applied to PNW oyster production?** Given the small number of studies on bivalve shellfish and complete lack of previous studies on PNW oysters, a key goal of this research is to pilot the development of a suitable LCA methodology.
2) **What are the relative environmental impacts of the main live oyster production methods?** There are various methods that can be used to culture oysters to harvestable size, creating different trade varieties of the same species of oysters. In this study, two different varieties of Pacific oysters (Classic Pacifics and Shigokus) were compared to analyze trade-offs between resource use and survival rate, and whether there is a difference in environmental impacts.
3) **What stage(s) of the process generate the most environmental impacts, and what scope is there for reducing them?** The oyster farming process consists of several subsystems that represent critical stages in the development and culture of oysters. A goal of this study was to determine which subsystems, if any, contribute the most to each type of environmental impact (or impact category). This information can be useful to growers searching for hotspot areas of the production process in which they can reduce their overall impacts to the environment, and for those aiming to become more environmentally friendly and resource efficient.
4) **Can oysters be justifiably marketed as a low environmental impact food?** The results of this data can be used by growers, retailers, and policy makers wishing to confirm or contest the sustainability of oyster production. Data from this analysis can be used to as concrete evidence to back up claims that oyster aquaculture, and bivalve production in general, is a low impact system.[53] By judicious comparison with other animal source foods (meat and poultry, wild-caught and farmed finfish), this LCA

> analysis can extend the conversation about the different food choices everyday consumers are familiar with, and how those options compare in terms of environmental impact.

The results of LCA studies are also relevant to the many environmental issues on the rise today, especially those associated with large industries. Climate change is a major issue of concern and therefore it is important for industries to calculate their greenhouse gas emissions; this will be important if, for example, governments begin to tax industries based on their carbon dioxide emissions. Life cycle assessment also provides data that can be used to address other industrial matters such as energy consumption, water use and the potential for pollution.[8] About 80% of the drinkable freshwater in the world is used for agriculture.[9] Intensive farming has been known to leach nutrients into nearby ecosystems, causing eutrophication and to generate toxic emissions, causing pollution and threats to human safety.[8] This analysis will provide quantitative data for each of these concerns, which in LCA, are reported in the form of 'impact categories', creating a basis for analyzing these broader resource depletion impacts.

These results will be important for seafood producers and distributors as well. This is especially true if the environmental impacts of oyster farming prove to be relatively low. Such information could be used to market oysters as a sustainable source of animal protein by providing new criteria not previously considered in ecolabels or policy decisions. This of course can only happen if the results of this LCA are comparable to other studies in terms of scope and methods. At the very minimum, this LCA will provide baseline information potentially used to promote public awareness concerning oyster aquaculture.

CHAPTER TWO

The Application of Life Cycle Assessment in Oyster Aquaculture

Methodology

Oyster farming in Washington

To conduct this life cycle assessment, information was sought out from a number of active farms in the Pacific Northwest region to give a comprehensive and inclusive look at shellfish aquaculture and to provide results that could be representative of the region. Due to time and resource restrictions and difficulties in securing commitment to an un-funded project, only one large company based in coastal Washington State was able to provide usable data. The company is well known and respected in the region and actively farms about 11,290,000 m^2 of beach for growing oysters, among other species of shellfish. It supplies various forms of oyster products to restaurants and retailers locally in Washington, across the United States, and even globally in Europe and Asia.[67]

The company's operations can be thought of an example of a 'steady-state' farm – it has been in production for about 60 years, when it first began farming the Pacific oyster (*Crassostrea gigas*) and the Olympia oyster (*Ostreola conchaphilia*) and is currently neither in the midst of expansion or contraction.[67] This minimizes the chance that the farm has not yet reached its ideal production potential, i.e. the inputs are directly related to the outputs of the systems. For all of these reasons, it was determined that this farm is an appropriate representation of large-scale oyster production with widely consumed products.

Description of the production process

The practices used in oyster aquaculture may vary according to geography or the end product type.[52] Even within similar regions or product types there may be some variation among the process that growers typically follow. Cultivation methods can vary from some light habitat management of self-seeded oyster reefs, to hatchery-based production of oysters that are then grown out in or on various artificial structures, such as mesh bags, wooden stakes, trellis tables, suspended trays or lanterns, and longlines.[46]

The company modeled in this life cycle assessment actively includes all production stages involved in oyster farming, and is entirely self-sufficient (it not only produces its own oyster seed, but it also sells seed to other growers as well). Hence, this life cycle assessment aims to include the entire production system as it relates to live Pacific oysters grown as single-seed products.

Oysters can be farmed as single-seed or cultched oysters. Cultched oyster larvae settle on broken pieces of shell (i.e. cultch) to create an oyster bed. As a result, the shells of new oysters unavoidably fuse to fragments of old oyster shell as they grow, making them harder to handle and less appealing to consumers. Consequently, these oysters are always sold as a shucked product. Single-seed oysters are grown as individual oysters (they do not develop in clumps of oysters or fused to old shell) and are sold live or as an individually quick frozen (IQF) product, usually on the half shell.[46]

There were several subsystems modeled in this LCA study: the hatchery, the FLUPSY (or Floating Upweller System), the grow-out phase (in this case on the beach), and processing. The output product of each subsystem serves as an input into the following subsystem. Product outputs are as follows: 2mm oyster seed, 6-12mm oyster seed, adult oysters, ending with live oysters on the half shell. Transport data between subsystems was also accounted for; resources for transporting product to the next stage in production were included within the subsystem in which that given product was grown.

Hatchery

The hatchery modeled in this study is a land-based operation located in Kona, Hawaii and consists of algal production and oyster seed production. A variety of algal species are raised in a matter of 10-15 days to serve as feed for developing oyster larvae. When oyster seed reaches a size of about 2mm, they are packaged and shipped via aircraft to the next subsystem in

California, taking about twenty-five trips per year. Truck delivery is utilized to bring seed from the airport to the FLUPSY which is located about twelve miles away from the airport.

FLUPSY

The FLUPSY serves as the nursey stage for 2mm oyster seed to grow to a large enough size that ensures better survival once they are put on the beach for grow-out, usually after about 1-6 months.[47] FLUPSYs are usually located in protected inlets and consist of a floating dock infrastructure latticed around many large aluminum bins suspended in the water below [Figure 2]. Oyster seed are placed in these bins, which contain a mesh bottom that protects them from predators while simultaneously allowing water to flow into the bins. Propellers generate an active current that provides nutrients to developing oysters and suspends the seed in the water column so that there is equal development and better overall survival. When the seed reaches a size of 6-12mm, they are packaged in insulated totes and brought to the beach for grow out via various sized trucks. The life cycle modeled in this study places each oyster seed through two different FLUPSYs before grow-out – the first is in California and the second in is Washington.

Figure 2. FLUPSY Subsystem Used in Oyster Aquaculture

Grow-Out

Two different methods of grow-out were modeled in this study, resulting in a comparison between two varieties of Pacific oysters: Classic Pacifics and Shigokus. The term ‘variety’ refers to the practice of beach-farming used to bring the oysters to maturity and sizable for consumption; they are still the same species of oyster and are not genetically different. Both varieties are placed on beaches all along the coast of Washington State and take about 2-4 years to grow, depending on the size of interest for harvest.[46]

Classic Pacifics are beach-grown, in other words they are strategically spread out upon coastal tidelands with appropriate substrate for survival and within an ideal range of changing tides. They require very little in terms of additional inputs or resources to grow. Shigokus, on the other hand, are a 'tide-tumbled' variety of Pacific oyster. In this method of grow-out, oysters are placed in mesh bags that are hung between posts. Attached to the mesh bags is a buoy that floats upwards with the incoming tide creating better water and nutrient circulation among oysters.[46] This is a more advanced technique that requires significant material inputs but allows for better protection and development and increases overall survival rate of the oysters.[67] It also produces a smoothed shell with a more regular shape that simplifies grading and packing and is more attractive to some consumers' taste and to some retailers, since they typically sell at a higher price than beach-grown Pacifics. Hence, one of the goals of this study is to discuss the trade-offs between Shigokus having higher materials inputs during grow-out compared to Classics (and therefore higher environmental impacts) but also having a higher overall survival rate – 80% versus 40%.[67]

Processing

Once oysters reach harvestable size, they are brought to the processing facility via truck or boat. Here they are cleaned and sorted by size – by hand for Shigokus and with grading machines for Classics. They are then packaged in preparation for transport to market. This demands the use of cardboard boxes, plastic mold trays to keep oysters upright, and freezer gel packs.

Scope, system boundaries, & functional unit

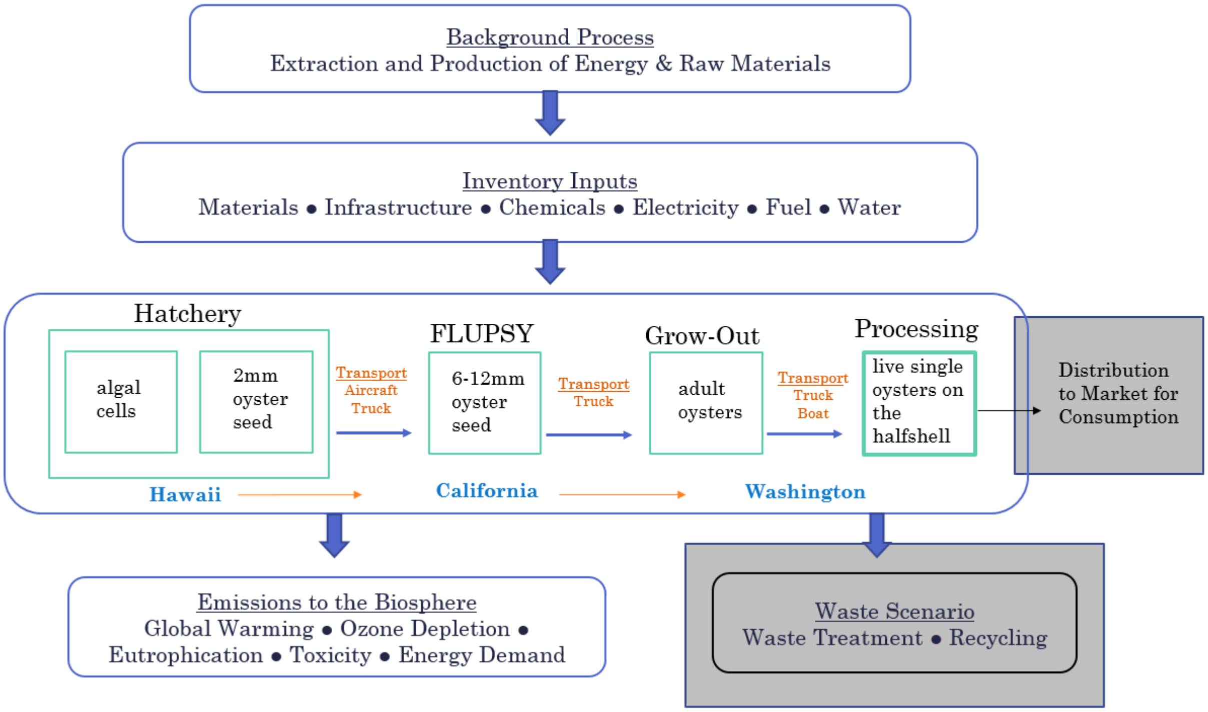
The methodology used in this life cycle assessment was in accordance with the requirements outlined in the ISO 14040 & 14044 series. These series of guidelines are written by the International Organization for Standardization, an international, independent Non-governmental organization with 163 national standards organizations as members (ISO).[68] The ISO requirements dictate systemic procedures and necessities for LCA practitioners to utilize in designing their studies. The series help minimize subjectivity in decisions on environmental impact and designate certain guidelines necessary for a legitimate life cycle assessment, creating a standard for nations and investigators worldwide.[69-70]

The scope of the study defines the system boundaries, the functional unit, and the methodology of the life cycle assessment.[1,28,29] The system boundary refers to the units and processes that are included in the life cycle.[1,29] I am using a cradle to retail-gate approach, beginning with feed production (algae) in the hatchery, and ending with live single oysters ready for distribution to market. More specifically, this includes the extraction and assimilation of raw materials and resources used to generate inputs into the system. Distribution is not included as this will be highly dependent on where the oysters are sent and how they are stored and handled in retail establishments, how the shells are subsequently disposed of and so on, which would be challenging to track or the numerous individual retailers. Waste scenarios, such as wastewater treatment or the recycling of used materials, were considered to be outside of the scope of the study. Figure 3 gives a more detailed look into system boundaries.

The current rise in seafood consumption is partly due to a higher demand for luxury items.[19] The sale of Pacific oysters continues to grow, and with this comes a shift from canned shucked meats to live oysters on the half shell as per consumer demand and the development of 'tide-tumbled' technology in oyster farming.[45-47] As people have increasingly shown an interest in fresh oysters on the half shell, this has driven many oyster farmers to produce single live oysters, or single-seed oysters.[71]

The functional unit is the referenced amount of product in which the system is quantified. I chose a dozen, live, single-seed oysters on the half shell because this reflects what is typically served at oyster bars and restaurants and is familiar to consumers. Using average oyster size and shell weight to meat weight ratios, this can easily be converted to kilogram of edible product to facilitate comparisons with other animal source food production systems. Alternatively, comparisons to average portion sizes in restaurants and in home consumption can also be made. For example, an individual consumer in Washington state consumers an average of 6 oysters in an order (when ordered by the dozen, oysters are often shared),[72] while average steak sizes may be 6 oz, so it makes sense to compare the environmental impacts of half dozen oysters with a 6 oz steak, though the quantity of meat, protein etc will differ. The important point is to be explicit about what comparison is being made.

Figure 3. System Boundaries and Description of the System Processes Analyzed in this Study.



Oysters sold in the market vary in terms of the shape of their shell and the quantity of their meat and water content, even within the same species and variety. For instance, in this study Shigokus are typically sold at a much smaller size than Pacifics, although size is not necessarily correlated to consumer preference. Even within the Classic Pacific variety of oysters the sizes in which they are sold range from ‘extra-small’ to ‘jumbo’.[67] Taking these considerations into account, it was determined that a function unit of ‘1 kg’ was not representative of the broader purposes of this research, which is to provide results that is generally relatable to people.

Company data from fiscal year 2016 was used as a representation of the most recent typical year’s production. The company produces several species of oysters and even other types of shellfish. Even within a given variety or species, various forms of product are generated, e.g. shucked, frozen, etc. Therefore, the resources used in oyster production are attributable to only a percentage of the company’s entire environmental impacts. Furthermore, many single processes (e.g. truck loads or algal production) include other species of shellfish such as clams or geoduck and so oyster farming alone was impossible to isolate as a single process. This would be the preferred method of allocating impacts to a specific product – known to LCA practitioners as 'system expansion'. Since oyster production is interlinked with the production of other shellfish, mass allocation was used when system expansion was not possible, as outlined in the ISO 14404 series. This means that the magnitude of the impacts associated with live Pacific oysters (carried out separately for Classics and Shigokus) correlate to their volume of production in proportion to the other farmed species and varieties. Mass allocation was used over economic allocation (assigning impacts based on their market value) as it illustrates the biophysical flows of materials and resources from one subsystem to the next.[73-74]

The carbon stored in oyster shells was not accounted for in this study, although oyster shells are made up of about 80-95% calcium carbonate.[50] Shells can be recycled to use for a variety of purposes including the production of quicklime used in construction, livestock feed supplement. In this case study, they are used as 'microcultch' for the setting of oyster larvae as seed – hence, they are recycled and reused within the system.[50-12] It should be noted, that de Alvarenga et al. (2015) conducted a life cycle assessment of oysters in Brazil looking at the recycling of oyster shells and found there to be significant reduction in impacts when accounting for this. While oysters are capable of long-term carbon storage within their calcified shells, they do not play a role in large-scale carbon sequestration. Oysters undergo cellular respiration to build their shells which releases carbon dioxide; CO_2 is also released as a byproduct of the calcifying process itself.[55]

Data Collection & Analysis

An LCA involves making an 'inventory' of materials, infrastructure and energy (electricity and fuel) inputs to the production system, as well as production outputs. Inventory data was collected via site visits and surveys. The survey was developed based on review of oyster farming practices, conversations with oyster farmers about their systems, and site visits to some of the oyster facilities (grow-out sites, processing sites, FLUPSYs) to see the production process. The survey was then was then left with the farm management team to complete. An excerpt from the survey used can be found in Appendix A. It was designed to elicit detailed information on the quantity, lifespan, and type of inputs – infrastructure, chemicals, materials (e.g. plastics, metals) and resources (e.g. energy use, freshwater use, fuel consumption) used in each subsystem. The Output data was also gathered on the quantity of product generated at the end of each subsystem (e.g. algal cells, seed, oysters). This information that describes the survival rates of each variety of oyster between each stage of growth and is critical for an accurate determination of impacts per dozen oysters. In other words, this accounts for the fact that 100% of the oyster seed grown in the hatchery do not make it all the way to the dozen oysters served in a restaurant. Production numbers are also the basis for allocating impacts to each variety of oyster, as described previously.

Seven categories of inventory inputs were analyzed for each subsystem (transport included): material, infrastructure, chemical, electricity, fuel, and water use. Inputs reported from the company were transferred to spreadsheets and converted to SI units of simple materials and resources used in a single year. For example, an input such as a sorting or shucking table can be reduced to 50 kg of aluminum. If this table has a lifespan of 25 years, then it would be entered as 2 kg of aluminum in the annual inventory scheme, so it is representative of typical annual production. To model energy consumption, data was collected on total kWh of electricity used by the shellfish farm for each subsystem as well as the specific electric companies used in different locations along the production process (e.g. Hawaii, California, & Washington). Total energy use was then allocated according to the percentage of each type of energy that the electric companies source from.

To translate these inventory inputs into environmental impacts associated with the production of a dozen live oysters, a software program called Simapro 8.1, was used. Simapro allows users to create a model of the production system and enter inventory data used in each subsystem. The software also houses various libraries that contain data on the background processes for each input (i.e. the extraction and production of raw materials and resources). The libraries include information on a wide variety of materials, chemicals, means of transport, etc. The ecoinvent 3.3 library, which is the most robust and widely applied, and the USLCI library, which contains more information on United States-based processes, were used in this life cycle assessment.[75]

There are various methods within Simapro that can be used to calculate the impacts of a production system. The ReCiPe Midpoint (H) version 1.13 / World Recipe H method was used for this analysis as it has relatively low uncertainty and is more commonly seen in LCA studies. The ReCiPe Method uses midpoint indicators that allow the results of the LCA to be aggregated into single environmental problems (in the form of impact categories) instead of general impacts to human health, biodiversity, and resources, as seed when using endpoint indicators.[76] The following impact categories were considered: global warming potential (GWP), ozone depletion potential (ODP), marine eutrophication potential (MEP), and human toxicity potential (HTP). The Cumulative Energy Demand (version 1.09) was also analyzed in this study. These categories are commonly used in LCA studies to discuss the different types of impacts to the environment that occur as a result of industrial processes.

CHAPTER THREE

Results & Discussion

Analysis of Results

Application of LCA & impact results

These results of the life cycle assessment for both varieties of oysters are summarized in Tables 1 & 2. Data on inventory inputs can be found in Appendix B, illustrating the quantities of materials and resources used to model the production system for both Classic Pacifics and Shigokus. Overall, Shigokus had slightly higher values for all environmental impacts than the Classic Pacifics, except for human toxicity potential, which was only slightly less than Classic Pacifics. This is especially true for the grow-out phase in which impacts for GWP, MEP, and HTP are different by an order of magnitude. Therefore, it cannot be concluded that Shigokus have a more favorable trade-off between environmental impacts and survival rate compared to Classics.

Table 1. Impact Assessment Results of the LCA of One Dozen Single Live Classic Pacific Oysters on the Half Shell

		Output (Subsystem)								
Impact Category	**Unit**	**2 mm oyster seed (Hatchery)**	%	**6-12 mm oyster seed (FLUPSY)**	%	**adult oysters (Grow-out)**	%	**live oysters on the halfshell (Processing)**	%	**TOTAL (at retail-gate)**
GWP	kg CO2 eq	7.36E-02	43	3.44E-02	20	2.54E-03	1	5.98E-02	35	1.70E-01
ODP	kg CFC-11 eq	9.42E-10	1	8.42E-08	80	1.21E-08	12	7.48E-09	7	1.05E-07
MEP	kg N eq	6.85E-06	27	7.08E-06	27	3.47E-07	1	1.15E-05	45	2.58E-05
HTP	kg 1,4-DB eq	3.91E-02	58	1.22E-02	18	6.20E-04	1	1.49E-02	22	6.69E-02
CED	MJ	3.94E+00	32	8.28E-01	7	6.55E+00	52	1.22E+00	10	1.25E+01

Table 2. Impact Assessment Results of the LCA of One Dozen Single Live Shigokus Oysters on the Half Shell

		Output (Subsystem)								
Impact Category	**Unit**	**2 mm oyster seed (Hatchery)**	%	**6-12 mm oyster seed (FLUPSY)**	%	**adult oysters (Grow-out)**	%	**live oysters on the halfshell (Processing)**	%	**TOTAL (at retail-gate)**
GWP	kg CO2 eq	5.59E-02	28	3.34E-02	17	2.69E-02	13	8.54E-02	42	2.02E-01
ODP	kg CFC-11 eq	6.96E-10	1	9.94E-08	82	1.45E-08	12	7.30E-09	6	1.22E-07
MEP	kg N eq	5.20E-06	15	6.41E-06	18	1.06E-05	30	1.28E-05	37	3.49E-05
HTP	kg 1,4-DB eq	3.00E-02	52	1.06E-02	18	2.74E-03	5	1.46E-02	25	5.80E-02
CED	MJ	4.52E+00	31	1.61E+00	11	7.41E+00	51	9.24E-01	6	1.45E+01

Transport data was accounted for in each subsystem as the energy, resources, and materials needed to get product to the next subsystem. In other words, impacts of seed shipment from the hatchery are attributed to the hatchery, seed leaving the FLUPSY to go the beaches for grow-out is accounted for in the FLUPSY subsystem. Transport of oysters leaving the beaches to be processed is included in the grow-out phase. There is no transport data included for processing since the system boundaries of this study end at the retail-gate, i.e. distribution transport is not included in this LCA.

Contribution of subsystems to impacts

There were differences in the percent contribution of each subsystems to the totals for each impact category [Figures 4 & 5]. Specific values highlighting the percent contribution of subsystems and total impacts are listed in Tables 1 & 2. Considering both varieties of oysters, the hatchery and processing contributed the most to GWP, the FLUPSY contributed the most to ODP, and grow-out contributed the most to CED.

During the grow-out phase, distinctions between the impacts of each subsystem per variety become more obvious. This is logical given that Classics require no additional inputs other than a few steel harvesting forks during their grow-out phase, whereas Shigokus require posts, bags, buoys, nylon rope, zip ties, etc. Hence, the impacts associated with grow-out of Shigokus have greater influence on overall environmental impacts than this stage of the process does for the Classics.

Figure 4. Percent Contribution of each Subsystem to Impact Categories for Classic Pacifics.

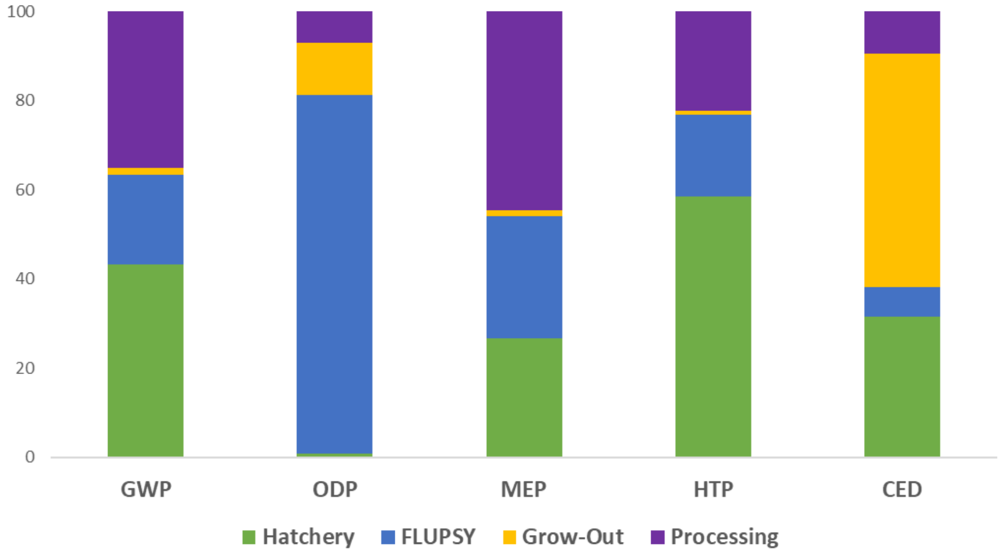
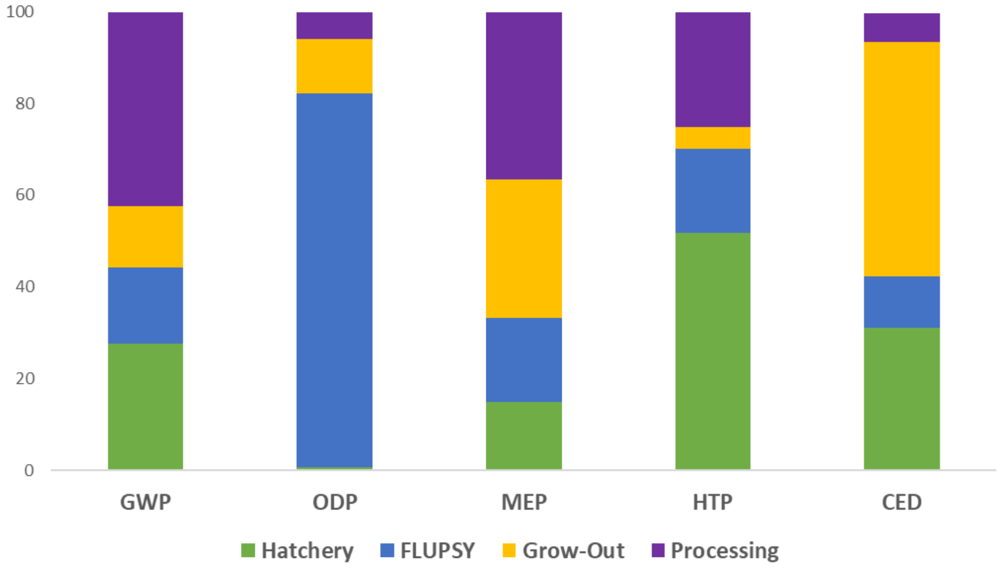


Figure 5. Percent Contribution of each Subsystem to Impact Categories for Shigokus.



A further breakdown of the sources of impacts in each subsystem is outlined in Figure 6, showing percent contributions to each impact category according to inventory type. Inventory types accounting for less than 1% of the total impacts for the subsystem are not shown. The exact percent contributions for each subsystem are contained in Appendix C. For Shigokus, material use account for much more of the total impacts associated with the grow-out phase versus the fuel used in transport. This is in contrast to Classic Pacifics, which shows fuel consumption having a higher influence than material use. However, even though there are noticeable differences between the two varieties during grow-out, they share similar sources of impacts for the rest of their life cycle. This makes sense given that they are otherwise farmed using similar methods.

Figure 6. Percent Contribution of Inventory Inputs to Subsystem Impacts

Throughout the entire production system for both varieties, fuel and electricity stand out as contributing the most to each impact category. Fuel is largely used during transportation, whereas electricity is used for lighting, refrigeration, ice machines, and water pumps. Impacts from chemical use (largely in the form of chlorine) are notable in the hatchery only. Water is mostly used during the processing stage for cleaning and ice production. Impacts from infrastructure are only visible in the FLUPSY stage; the resource demands of this subsystem are dominated by long-lasting infrastructure, with small plastic buckets as the only material input.

The processing stage had the widest range of inventory types as contributor to impacts; chemicals were the only input not represented. All inventory types except infrastructure made more than a 1% contribution to impacts in the hatchery, with fuel as the dominant influence. Infrastructure, electricity, and fuel were the main contributors to the FLUPSY impacts, and only material and fuel use contributed to the grow-out phase.

Discussion

While this production system is by no means simple or small, the ratio of product output to resource inputs is high – as is often typical within large-scale practices. Oysters raised from seed, as in this case study, are fed algae grown in the hatchery. However, the startup amount of algae taken from nature is as little as 50mL every few years.[67] During the nursery and grow-out phases, long-lasting materials and infrastructure are the primary inputs into these systems, and there are no additional resource demands while oysters are maturing – they are simply tossed on the beach or placed in bags on the beach and then harvested once they reach market size.

The placement of the hatchery in Hawaii also reduces environmental impacts. Warmer weather and abundant sunshine (compared to Washington) result in lower electricity demands for heating and lighting. Warm water taken from the ocean does not need to be heated and no artificial indoor lighting is used. However, it could be argued that transport between the island and the continental U.S. negates this energy saving, especially since fuel contributes to over 60% of the values for all impact categories except ODP. Too add to this, there is concern as to whether the “food miles” in which transportation energy costs are based upon is too general, assuming costs are directly correlated to distance traveled, and perhaps the role of fuel as a main contributor to impacts is even greater.[53] That said, it is possible that the small size and large number of oyster seed sent in relatively few trips may not be as inefficient as it seems given the low values of each impact category within the hatchery.

It is likely that the main reason oyster farming has very low impacts, especially when compared to other aquaculture production, is that it is not a fed-system. Typically, feed production makes up a major portion of the environmental demands in aquaculture systems.[17,32,53] Oysters, and bivalves in general, are low-trophic level species and do not need any feed inputs into the system as do other intensive aquaculture systems such a farmed salmon.[53] Rather, they filter feed plankton from the natural environment.[54]

Oysters have been analyzed through an LCA or carbon footprint perspective in both Brazil and Europe. This study represents large-scale oyster aquaculture in North America where it is especially prevalent along the Pacific Northwest of the U.S. and Canada. Changes in geography within a specific type of food system is important, especially in terms of energy use. The results of this LCA highlighted electricity as a notable contributor to environmental impacts, and the means used to generate the electricity sourced by the production system can make a huge difference in magnitude of the impacts.[17] About 84% of the electricity in Washington State is generated via hydropower, which is much cleaner in terms of emissions than non-renewable (fossil fuel) energy sources.[77,20] Since most of the electricity consumption for oyster farming takes place in Washington, this influences the LCA analysis.

How does this relate to everyday food choices?

The primary aims of this study were to develop a method for LCA analysis applicable to North American oyster farming and pilot the methodology by performing an attributional life cycle assessment of an oyster farm based in Washington. This study provides a methodological framework for other such studies and critical baseline data that can be translated into a relatable context for consumers. In other words, comparing the environmental impacts of different food systems collected from attributional studies, gives LCA results meaning to consumers and retailers looking to make sustainable food choices. There is discussion in LCA literature around including the nutritional value of the product in life cycle assessments. This is seen in the evolution of functional units used in life cycle assessment from a mass-based focus towards a nutritional basis, with, for example, comparisons of the environmental costs of producing a typical daily recommended requirement of protein.[34,78]

However, given the scope of this study and the fact that live oysters on the half shell are likely not a dependent source of protein for most people living in Washington State, but rather a luxury good for restaurant goers, it makes sense to compare oysters in a context that is most closely in line with the latter scenario. Table 3 describes the global warming potential (GWP) of different food sources in relation to the standard recommendations for serving size by the United States Department of Agriculture (USDA) and to what may typically be eaten per individual in restaurants or in homes. Data from this study was used to represent oysters (averaged between the two varieties), and data for all other food sources were based on other individual LCA analyses and reviews. Comparing oysters to other food systems, the largest differences in kg-CO_2 emitted per serving size in seen in comparison to beef and pork. Beef especially, has a much higher GWP overall compared to other foods, even among the standard 3 oz. serving size. Oysters have a very similar GWP to mussels, illustrating the idea that bivalves are indeed a relatively low-impact system.

Table 3. GWP in kg CO_2-eq for Different Animal Source Foods in Relation to Everyday Consumption.

Live Oysters	**Fresh Mussels**[64]	**Farmed Salmon**[79]	**Chicken**[80]	**Pork**[81]	**Beef**[82]
Half Dozen[72]	Standard 3 oz. Serving[83]				
0.1	0.08	0.18 - 0.33	0.12 - 0.19	0.38	0.75 - 2.9
Dozen	8 oz. Mussels	6 oz. Fillet	6oz. Roast Chicken	6 oz. Pork Chop	8 oz. Burger
0.19	0.22	0.36 - 0.66	0.24 - 0.38	0.77	2.0 - 7.74
					12 oz. Steak
					2.99 - 11.59

Limitations of this study

This LCA was based on a single company for one year of production in 2016. The study could be augmented by including more oyster farms and generating an average impact analysis for the PNW oyster sector, with indications of the degree of variability between farms and production/grow-out systems. Similarly, although the production year modeled in this study was typical and expected compared to previous years,[67] including data from multiple years could potentially increase the accuracy of the data, as there is often some year to year variation in production.[84] Within oyster farming, the development of innovative techniques that improve survival rates of oysters – as seen with Shigokus – which will improve the inputs to outputs ratio, an reduce environmental impacts. There is also natural variation in survival rates from year to year, driven largely by weather and water composition, e.g. food richness, harmful algae, acidification, uncommon temperatures. Additionally, variations in product type within oysters (frozen, live, shucked), could be analyzed in an LCA study to determine which product form has the lowest impacts. However, this variation is likely negligible, as oyster farming in general is still a relatively low input system. Furthermore, this study represent large-scale production, there are still many small artisanal farms in existence that may have an even lower environmental impact, although this cannot be assumed.

Many reviews of the life cycle assessment processes have noted the need to include studies that expand system boundaries to look beyond the retail-gate and include end-of-life and waste processes.[36] This analysis could be further explored to include the distribution of oysters to market and waste scenarios. This is especially important for large-scale production such as this, in which product is shipped to several different parts of the country and the world. This would allow an analysis of ideal transport distance, mode, and frequency; e.g. how are the impact trade-offs different (if at all) if a company decides to send oysters in a few very large shipments to Asia versus sending oysters to local farmers' markets in fewer and much more frequents trips but with significantly shorter distances?

Conclusion

Life cycle assessment was used to analyze the environmental impacts of live oyster farming in the Pacific Northwest. Different methods of grow-out result in different impacts to the environment: tide-tumbled oysters have a higher resource demand even though they have a better survival rate compared to beach-grown oysters. Each subsystem within the production system made a visible contribution to impacts, although the extent of this contribution varied over different impact categories. The results of this life cycle assessment can be communicated to growers, retailers, and consumers to help make more informed decisions regarding sustainable food choices.

CHAPTER FOUR

Socioeconomic Dimensions of LCA

Method development of assessing social and economic indicators

Currently, the standard methodology of life cycle assessment fails to systematically include ways to address socioeconomic impacts. As a result of this, there is an apparent and growing need for these considerations to be included in the discussion of sustainability. Many studies reviewing the life cycle assessment methods have mentioned this need to include socio-economic data for a more comprehensive understanding of production systems.[17,33,35] There are ongoing research efforts directed towards devising potential frameworks to use.[84,19-20] However, relatively little has been done to carry these efforts through into action and the field remains largely underdeveloped. What has been done is more of a qualitative analysis, rather than the quantitative structure that defines life cycle assessment. Hence, there remains an obvious gap in the spectrum of sustainability analysis.[19-20]

Including social and economic factors in our definition of sustainability is critical to achieve equity and environmental stewardship simultaneously. Ziegler et al. (2016) states that the ultimate goal of sustainability assessment should be to optimize social benefits while lessening environmental impacts as much as possible. Within food production systems, social considerations may include cultural valuation of the practice, working conditions, and benefits to consumers and other stakeholders.[85] Measuring impacts to the economy and employee salaries is also an important aspect of the production system. As is the case with oysters, this product is associated with long-standing cultural tradition and economic profit.[47] Developing a sound method to evaluate these considerations will help answer fundamental social and economic questions. For instance, how does the quality of life of a worker at the assembly line of an industrial slaughterhouse compare to that of a fisherman out in the middle of the ocean catching seafood? Who has a higher risk for injury? Who makes more money? What is the sense of livelihood or tradition versus it being ‘just a job’?

There are several promising methods to create a more comprehensive LCA process and progress towards doing so is evident, but there is also some inconsistency in terminology and approach. Most often, practitioners are combining methods to create a systematic approach. This is a positive start but far from creating a single triple-bottom-line tool for determining social, economic, and environmental impacts. In 1996, a general framework was developed by O'Brien et al. (1996) that could serve as the groundwork for the future development of impact categories and characterization factors, which are key to producing analysis results. The United Nations Environment Programme issued a report in 2009[85] providing a framework for social life cycle assessment (SLCA), with suggested impact categories, including: working hours, forced labor, transparency, local employment, respect for indigenous rights, and corruption. These were divided among various stakeholders: workers, local communities, society, consumers, and value chain actors. Life cycle costing (LCC) has been used to evaluate economic factors. LCC is a similar tool to LCA but instead of measuring environmental impacts throughout the production unit, it measures monetary costs.[87] Some researchers have looked at including data envelopment analysis (DEA) with traditional LCA as a way of including socioeconomic considerations.[84,88-89]

Attempts to model socioeconomic LCAs

With no standard comprehensive method of including triple-bottom-line indicators in life cycle assessment, there are only a number of studies that attempt to perform an LCA using social and economic methods, and even fewer on food systems. It is also important to point out that methods such as the UN & SETAC's framework for SLCA only provide impact categories and currently there is no formal way of characterizing impacts. For instance, an SLCA study on Canadian dairy farming used this method to define their impact categories and when it came to analyzing each one for results they used an evaluation scale, with binned categories similar to that of a Likert scale.[90] Therefore, there is some subjectivity inherent in this process. Another study on the sugar industry in South Africa collected data via surveys and interviews and followed a similar method to characterize impacts related to gender equity, wages, and health and safety. The authors were able to make policy recommendation to improve equity and working conditions based on their results.[91] Vavra et al. (2015) took a slightly different approach when modeling food industries in the Czech Republic. They used a number of impact categories such as fair competition and fair salary (obtained from the UN & SETAC framework) and determined the percentage of stakeholders' valuation of these categories ranging from 'less important' to 'very important'.[92]

It is essential that these socioeconomic considerations are made with respect to the final product being analyzed in the life cycle, i.e. the functional unit. As noted by Dreyer et al. (2006), the social and economic costs of the production system should correlate with the additive environmental costs along the chain of processes within the system.[93] In regards to seafood production, Kruse et al. (2009) used both descriptive and additive indicators in their analysis of the salmon industry.[94] Descriptive impact categories included 'right to organize', 'discrimination/gender', and 'employment benefits'. Additive impact categories include the 'costs to produce one functional unit (FU)', 'the loss of life/injury on the job per FU', and 'the total person hours required to produce one FU'.

While efforts have been made to evaluate socioeconomic concerns along with environmental costs, there is still a lot of progress to be made before it becomes standardized in the LCA method. Specifically, the difficulty remains in characterizing socioeconomic impact categories using a systematic framework. This along with the fact that social and economic considerations may vary much more than environmental costs from company to company, even within the same type of production system.[95] Nonetheless, work continues to be made to expand upon current frameworks and innovate new methods of assessing triple-bottom-line impacts using life cycle assessment.

Appendix A

1. What was this land used for prior to oyster farming? ___________________________
    a. How was the land changed to prepare for oyster farming?

    ____

B. Oyster Production

1. Was the fiscal year 2016 [FY 2016] a typical year for oyster production? _________
    a. If not, please note and answer for the most typical production season and indicate this unit for the remaining questions

    ____
2. How many shucked oysters were produced/harvested in FY 2016? ______________
3. How many years have you been producing shucked oysters? ____________________

For each of the following questions please respond for each variety of live single oyster. Do this by filling out the table below.

4. How many live single oysters of each variety were produced/harvested in FY 2016?

    After processing …

    a. Of these, how many were sold to market? (number of oysters or percentage of value in B.4.1 acceptable)
    b. How many were lost? (number of oysters or percentage of value in B.4.1 acceptable)
5. How many years have you been harvesting each variety of single oysters?
6. How many total acres of beach were harvested for each variety of single oysters in FY 2016?
7. What methods are used to produce each variety? (be specific but consistent; e.g. beach culture, grow-bags bottom culture, tumble bags, etc.)

Section 3 – Grow-out Techniques

A. Land Preparation

1. Are pesticides applied to the beach prior to oyster farming? _________

If yes…

   a. Type / Name ____________________________________

   b. Volume _______________________________

   c. Frequency ______________________________

   d. For which beaches/varieties of oysters?

   ____

   ____

2. Are there any other changes made to land before it is occupied by oysters? If yes, please describe.

   ____

   ____

B. Methods & Materials

1. Please fill out the following table:

Culture Technique Used:	**Acres of Beach Designated for this Method:**	**Percentage of Single Oysters Produced from this Method:**
Beach grow-out		
Grow-bags (on beach)		
Tide-tumble Bags		
Other:		
Other:		

Appendix B

Inventory Inputs for Classic Pacifics per Subsystem.

	Hatchery	FLUPSY	Grow-Out	Processing
Materials				
low-density polyethylene	6.11 kg			
high-density polyethylene	0.79 kg			
glass fibre reinforced plastic	0.57 kg			
glass	0.15 kg			
steel, low-alloyed			184 kg	6,854 kg
polyvinylidenchloride				
polyurethane, rigid foam				145.80 kg
acrylonitrile-butadiene-styrene copolymer		3.81 kg		
polypropylene				1,138.40 kg
polystyrene				6,618 kg
cardboard				141 kg
nylon 6-6				
Infrastructure				
zinc coat, pieces		7.82 m^2		
alluminum, alloy		2,004.61 kg		27.90 kg
steel, chromium steel 18/8		22.14 kg		
steel, low alloyed	118.24 kg	580.14 kg		
polypropylene		539.93 kg		
linear low density polyethylene		0.34 kg		
polyvinylidenchloride	0.07 kg	1.41 kg		
glass fibre reinforced plastic	0.33 kg			
glass	1.60 kg			
synthetic rubber	0.04 kg			0.30 kg
wood		21.33 kg		
Chemicals & Solutions				
chlorine	53,132.80 oz			
bleach	34.94 oz			
hydrochloric acid	135.86 oz			
Dawn soap				126.36 oz
sanite 75F				20.22 oz
Duchess 425				35.38 oz
Supersan				328.54 oz
2% sodium polyacrylate (gell packs)				2,753 kg
Electricity				
	149,487 kwh (HELCO)	108,857 kwh (PG & E; PUD 3)		876,504 kwh (PUD 3)
Fuel				
Gasoline		419 gal		
Propane				842.40 gal
Water				
	374,948 gal			10,810,800 gal
Transportation				
2% sodium polyacrylate (gell packs)	5.85 kg			
airplane miles	0.003 kgkm			
truck miles	172.20 mi			
cardboard	0.08 kg			
polystyrene foam	301.35 kg			
gasoline		48,717.6 gal	7,279.64 gal	
polyurethane, rigid foam		23.25 kg		

Inventory Inputs for Shigokus per Subsystem.

	Hatchery	FLUPSY	Grow-Out	Processing
Materials				
low-density polyethylene	1.41 kg		438 kg	
high-density polyethylene	0.18 kg		1,958.90 kg	
glass fibre reinforced plastic	0.13 kg			
glass	0.03 kg			
steel, low-alloyed				245 kg
polyvinylidenchloride			1,518 kg	
polyurethane, rigid foam			572 kg	43.20 kg
acrylonitrile-butadiene-styrene copolymer		0.88 kg		
polypropylene				513 kg
polystyrene				6,406 kg
cardboard				34.40 kg
nylon 6-6			278.20 kg	
Infrastructure				
zinc coat, pieces		1.80 m^2		
alluminum, alloy		460.99 kg		87.60 kg
steel, chromium steel 18/8		5.09 kg	54.50 kg	
steel, low alloyed	27.19 kg	133.41 kg		
polypropylene		124.17 kg		
linear low density polyethylene		0.08 kg		
polyvinylidenchloride	0.02 kg	0.32 kg		
glass fibre reinforced plastic	0.08 kg			
glass	0.37 kg			
synthetic rubber	0.01 kg			0.09 kg
wood		4.91 kg		
Chemicals & Solutions				
chlorine	12,218.70 oz			
bleach	8.03 oz			
hydrochloric acid	31.24 oz			
Dawn soap				37.44 oz
sanite 75F				5.99 oz
Duchess 425				10.48 oz
Supersan				97.34 oz
2% sodium polyacrylate (gell packs)				1,247 kg
Electricity				
	34,377 kwh	25,033 kwh		259,705 kwh
	(HELCO)	(PG & E; PUD 3)		(PUD 3)
Fuel				
Gasoline		96.36 gal		
Propane				249.6 gal
Water				
	86,225 gal			3,203,200 gal
Transportation				
2% sodium polyacrylate (gell packs)	1.3464 kg			
airplane miles	0.000587 kgkm			
truck miles	39.60 mi			
cardboard	0.0000000615 kg			
polystyrene foam	69.30 kg			
gasoline		17,491.79 gal	2,613.7 gal	
polyurethane, rigid foam		5.345 kg		

Appendix C

Percent Contribution of Inventory Categories to Impacts of Each Subsystem for Classic Pacifics and Shigokus.

Global Warming Potential (GWP)

	Hatchery		Flupsy		Grow-Out		Processing	
	Classics	**Shigokus**	**Classics**	**Shigokus**	**Classics**	**Shigokus**	**Classics**	**Shigokus**
infrastructure			18.1	14.4				
materials					4	89.3	45.1	61.5
chemicals	1.7	1.8						
electrcity	2.1	2.1	32.6	25.8			32.3	22.4
fuel	93.6	94.9	47.5	58.5	96	10.7	1.3	
water							20.6	14.3

Ozone Depletion Potential (ODP)

	Hatchery		Flupsy		Grow-Out		Processing	
	Classics	**Shigokus**	**Classics**	**Shigokus**	**Classics**	**Shigokus**	**Classics**	**Shigokus**
infrastructure								
materials	2.6					1.5	4.1	1.9
chemicals	76.2	79.3						
electrcity	16.2	16.9	2.2	1.5			85.9	87.4
fuel	1.3		96.3	97.5	99.9	98.5		
water	2.6	2.7					9.6	9.7

Marine Eutrophicaiton Potential (MEP)

	Hatchery		Flupsy		Grow-Out		Processing	
	Classics	**Shigokus**	**Classics**	**Shigokus**	**Classics**	**Shigokus**	**Classics**	**Shigokus**
infrastructure			31.4	26.6				1.7
materials	1.2				6.3	96.4	23.1	29.8
chemicals	5.2	5.3						
electrcity	7.8	7.7	36.9	31.9			53.5	47.8
fuel	84	85.2	30.8	40.7	93.7	3.6		
water		1.3					22.2	19.9

Human Toxicity Potential (HTP)

	Hatchery		Flupsy		Grow-Out		Processing	
	Classics	**Shigokus**	**Classics**	**Shigokus**	**Classics**	**Shigokus**	**Classics**	**Shigokus**
infrastructure			61.1	54.2				6
materials					33.8	82.3	12.7	6
chemicals	1.8	1.8						
electrcity	5.2	5.3	15.2	14.6			52.8	53.4
fuel	91.9	92.1	22.5	31.1	66.2	17.7	4.3	4.4
water							29.5	29.9

Cumulative Energy Demand (CED)

	Hatchery		Flupsy		Grow-Out		Processing	
	Classics	**Shigokus**	**Classics**	**Shigokus**	**Classics**	**Shigokus**	**Classics**	**Shigokus**
infrastructure			5.5	3.7				
materials	1.7					39.6	18.4	29.5
chemicals	1.6	1.6						
electrcity	19	19.4	7.7	5.3			73.6	63.5
fuel	77	78.4	84.6	89.4	99.8	60.4	3.3	2.9
water							4.4	3.8

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