Food-Energy-Water Nexus:

Opportunities to Enhance Sustainability of Aquaculture and Aquaponic Systems Using Life Cycle Assessment

By

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Abstract

The world food demand is significantly increasing due to the growing population (from 7.55 billion in 2017 to as estimated 11.18 billion by 2100) and per capita food consumption (2358 calories in 1965 to 3180 calories in 2030). In order to meet the ever-increasing demand for food, humans have developed and expanded intensive agriculture practices (along with other food production strategies). These practices have resulted in a significant increase in total production quantity and average yield with respect to food production, however, it has also resulted in a significant pressure on the ecosystems' primary elements such as land use (e.g. harvesting area) and water consumption (e.g. irrigation).

To mitigate the environmental impacts of massively increasing food production (e.g. intensive freshwater use, energy consumption, etc.) while addressing the growing demand to food, there is a need to embrace the complexity of sustainable food production through a systems thinking approach. It means that a holistic evaluation of impacts, utilizing varying indicators and production aspects, is necessary to point out stabilized solutions to the sustainable food provision challenges.

The implementation of industrial ecology in the food-energy-water nexus implies tightening food production cycles, which enables us to produce more food with less resources use (e.g. water) and minimized emitted waste and damages to ecosystems (such as nutrient pollution). Considering that, aquaponic food production is one potential solution to increase food production capacity. In aquaponics a seafood-producing environment (aquaculture) is integrated with a soilless plant-producing environment (hydroponics) with nitrifying and mineralizing bacteria serving as a filter in a symbiotic recirculating setup. Combining these systems is anticipated to be a more environmentally and economically sustainable food production process compared to separated conventional agriculture and seafood harvesting. However, quantified assessment of these promising systems is required to (1) highlight the potential burden shifting that may occur due to aquaculture production intensification in aquaponics, and approaches to prevent it, (2) identify the environmental impact hotspots, and strategies to further mitigate the environmental impacts associated with aquaponics, and (3) recognize practical scenarios to elevate aquaponic food production, integrating economic consideration, varying decision-making approaches, and food transportation implications. To address the aforementioned points, I quantitatively evaluated varying aspects of aquaponic food production, with a focus on cold-weather production in this dissertation.

In the first study (Chapter 2), eighteen Life Cycle Assessment (LCA) studies were reviewed which included assessments of recirculating aquaculture systems (RAS), flow-through systems, net cages, and pond systems. This review considered the potential to mitigate environmental burdens with a movement from extensive to intensive aquaculture systems. Due to the diversity in study results, specific processes (feed, energy, and infrastructure) and specific impact categories (land use, water use, and eutrophication potential) were analyzed in-depth. The comparative analysis indicated there was a possible shift from local to global impacts with a progression from extensive to intensive systems, if mitigation strategies were not performed. The shift was partially due to increased electricity requirements but also varied with electricity source. The impacts from infrastructure were less than 13% of the environmental impact and considered negligible. For feed, the environmental impacts were typically more dependent on feed conversion ratio (FCR) than the type of system. Feed also contributed to over 50% of the impacts on land use, second only to energy carriers. The analysis of water use indicated intensive recirculating systems efficiently reduce water use as compared to extensive systems; however, at present, studies have only considered direct water use and future work is required that incorporates indirect and consumptive water use. Alternative aquaculture systems that can improve the total nutrient uptake and production yield per material and energy-based input, thereby reducing the overall emissions per unit of feed, should be further investigated to optimize the overall of aquaculture systems, considering both global and local environmental impacts. While LCA can be a valuable tool to evaluate trade-offs in system designs, the results are often location and species specific. Therefore, it is critical to consider both of these criteria in conjunction with LCA results when developing aquaculture systems.

In the second study (Chapter 3), a comprehensive cradle-to-gate life cycle assessment utilizing multiple midpoint environmental impact categories (such as eutrophication potential and greenhouse gas emissions) was performed on a case study aquaponic system, which cultivates multiple vegetable species as well as carnivorous hybrid walleye. This provided the opportunity to investigate the environmental impacts of using closed-loop aquaponics in a cold weather setting. The main contributors of the system's environmental impacts were recognized: heat, electricity, equipment, and fish food contributed to >88% of environmental impacts in all investigated categories. Finally, alternatives using different real-case scenarios (effective space heating, equipment lifespans, fishmeal-free 31diet, etc.) were proposed and evaluated. This work sought to inform the discussion as to the environmental considerations of aquaponic food production.

In the third study (Chapter 4), a holistic life cycle impact assessment of twelve formulated and utilized aquafeeds has been performed to provide a comparative evaluation of different aquafeed’s environmental impacts, considering resource use (biotic resource use, water intake, and fossil fuel depletion) and emission-based impact categories (ozone depletion, global warming, photochemical smog, acidification, eutrophication, carcinogenics, non-carcinogenics, respiratory effects, and ecotoxicity). Results indicate that the investigated fish meal free diets do not, on the whole, result in a significant decrease in environmental impacts with respect to the use of biotic resources. However, if the substituted ingredients would not propose elevated impacts (e.g. blood meal), these diets can potentially lower the overall environmental impacts of aquafeed production mainly with respect to relevant emission-based indicators (e.g. global warming, eutrophication, ecotoxicity). Findings demonstrate that the investigated fish oil free diets can potentially lower the use of biotic resources. However, to prevent burden shifting, strategies to provide nutrient-rich oils with minimal energy requirement need to be undertaken.

In the fourth study (Chapter 5), to holistically evaluate the environmental and economic implications of aquaponics, specifically in a cold-weather climate, Life Cycle Assessment and Economic Analysis were performed on a cold-weather located aquaponic system, using data from three years of annual operation cycles with varying fish species production; tilapia, conventional walleye, and hybrid walleye. For the LCA, environmental impacts were quantified using 10 midpoint indicators. Assessments indicated that 1-kilogram production of live-weight tilapia, conventional walleye, and hybrid walleye resulted in 20.2-13.8-11.7 kg CO2-eq, 23.0-7.8-3.9 g N-eq, and 0.2-0.3-0.4 kg SO2-eq, consecutively, using the investigated system. The most sensitive parameters for environmental impacts were heat, aquafeed, electricity, and infrastructure (in all scenarios). For EA, benefit to cost ratios (BCRs) and three other widely used indices were analyzed for production cycles. The BCRs were 0.47, 1.16, and 1.75 for tilapia, conventional walleye, and hybrid walleye, respectively (using a 10% discount rate and a 20-year horizon); highlighting the necessity of optimizing both cash inflows (e.g. energy costs) and outflows (plant and fish revenues) to achieve practical enhancement of return on investments. The cost major contributors were infrastructure, labor, and heat (contributing to > 89% of total costs for all cycles). Suggested steps for in-effect improvement of the investigated aquaponic system’s environmental and economic favorability include heat and infrastructure optimization by: (a) applying effective heating strategies (e.g. advanced insulation techniques), and (b) expanding system’s operational lifespan (e.g. prevention of waste accumulation).

The fifth study (Chapter 6) provided a multi-dimensional assessment of current and promising future aquafeeds, utilizing multi-criteria decision analysis (MCDA). The considered parameters included cost, environmental impacts, and nutrients inclusion. Results based on varying stakeholders’ perspectives indicated that the replacement of fish meal with plant-based soybean

meal, and fish oil with plant-based canola oil are the most favorable alternatives among those investigated to elevate the overall aquafeed performance in aquaculture food production.

In the final study (Chapter 7), I showed that disregarding the environmental impacts of seafood transportation, either land transit or flight, neglects a significant portion of total seafood provision environmental impacts. We identified that local seafood provision, considering (1) all Wisconsin counties as production points, (2) cities of Chicago, Milwaukee, and Minneapolis as consumption points, and (3) effective, semi-effective, and ineffective space heating approaches, has significantly lower environmental impacts than non-local seafood provision, considering flight transportation from offshore production points. Hence, the necessity to elevate local seafood production capacity to enhance the environmental sustainability of seafood provision is essential, despite potential elevated heating demands for cold-weather aquaculture. Expanding assessments' system boundary to include transportation inventory is essential to provide a comprehensive environmental evaluation to inform prospective policy actions and potential trade-offs for local seafood provision.

In sum, this work seeks to fill the current gap in the body of knowledge to provide a holistic system-level approach to evaluate different aspects of elevating sustainable food production, focusing on seafood, by undertaking potential mitigation strategies including system intensification (intensive aquaculture), system integration (aquaponics), alternative feeding, and local production.

Dedication

I dedicate this thesis to:

My mom, my first, best, and forever friend. Thank you for your endless love, sacrifices, prayers, support and advice. I love you.

Acknowledgement

The fact that I am at the stage of writing this thesis has a clear meaning: surviving years of being out of comfort zone and pushing boundaries, hard work and dedication to research, and persistence to the face of all coherent challenges in a PhD program. Going through this rewarding journey has become possible with the support of the following individuals, whose assistance and inspiration has been invaluable in the completion of this dissertation.

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In the end, I would like to recognize the invaluable assistance that anyone provided during my study, who may be missed from my list. I wish to be able to pay forward all the support I have received upon the completion of this thesis, which is an incredibly challenging resolution given the tremendous support I received throughout my PhD journey.

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Abbreviations

Acronym	Full Phrase
a	per annum
ACP	Acidification Potential
BCR	Benefit-to-Cost Ratio
BOD	Biological Oxygen Demand
BRU	Biotic Resource Use
C	Specific Heat
Cal	Calorie
ECP	Ecotoxicity Potential
EPA	Environmental Protection Agency
eq	Equivalent
EUP	Eutrophication Potential
FAO	Food and Agriculture Organization
FCR	Feed Conversion Ratio
FFP	Fossil Fuel Depletion Potential
GHG	Green House Gas
GWP	Global Warming Potential
HHCP	Human Health Carcinogenics Potential
HHNCP	Human Health Non Carcinogenics Potential
IL	Illinois
IMTA	Integrated Multi-Trophic Aquaculture
IRR	Internal Rate of Return
ISO	International Standard Organization
kg	kilogram
kJ	kilo Joule
km	kilometer
km	kilometer
LCA	Life Cycle Assessment
M	Mass
m	meter
MN	Minneapolis
N/A	Not Applicable
NPV	Net Present Value
ODP	Ozone Depletion Potentials
PBP	Payback Period
PSP	Photochemical Smog Potential
Q	Thermal Energy
RAS	Recirculating Aquaculture System
REP	Respiratory Effects Potential
SC	Scenario
SI	Supplementary Information
T	Temperature

TP	Total Phosphorus
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
TSS	Total Suspended Solids
USLCI	United States Life Cycle Inventory
V	Occupied space
WI	Wisconsin
ρ	Density

1. Chapter 1: Research Objectives

This work seeks to fill the current gap in the body of knowledge of sustainable cold weather aquaculture, but addressing the following objectives:

- Evaluate potential burden shifting by the intensification of aquaculture systems, and the prospective approaches to prevent it (Chapter 2).
- Determine the quantified environmental impacts of aquaponic food production using Life Cycle Assessment in a cold weather location (e.g. Wisconsin; producing multiple vegetable species as well as carnivorous hybrid walleye), and utilizing a comprehensive inventory and considering multiple impact categories (Chapter 3).
- Inform practical strategies to elevate the sustainability of cold-weather aquaponic food production by jointly analyzing environmental and economic implications of the aquaponic system (Chapter 5).
- Perform a comprehensive evaluation of the environmental sustainability of aquafeeds with respect to variable ingredients, both in terms of resource use and waste emission, using comparative Life Cycle Assessment of the current and promising feeding formulations for aquafeed production (Chapter 4).
- Apply Multi-Criteria Decision analysis to aquafeed selection using data derived from aquafarmers, to evaluate prospective strategies to move towards more sustainable aquafeeds considering other in-practice considerations (e.g. cost, efficacy, etc.) along with environmental implications (Chapter 6).
- Perform a spatially explicit analysis of the environmental impacts associated with fish food provision and transportation offsets in Wisconsin, to determine the tradeoffs of local cold weather food production with respect to heat and transportation compared to warm weather food production (Chapter 7).

These six objectives contribute to the overall driving question behind this research: is aquaponics a sustainable cold-weather food production system?

This is critical, as the mitigation of vulnerability in food systems, to ensure healthy food for all, requires a deep investigation on the best approaches to tackle the challenges associated with the promising food provision systems (e.g. environmental burdens). This research is intended to significantly move the state of knowledge and the discussion as to whether aquaponics could be a prospective sustainable food production strategy, especially in cold weather regions such as Wisconsin.

2. Chapter 2: Life Cycle Assessment of Aquaculture Systems: Does Burden Shifting Occur with an Increase in Production Intensity?

This chapter was adapted from: Ghamkhar, R., Boxman, S. E., Main, K. L., Zhang, Q., Trotz, M. A., & Hicks, A. (2020). Life Cycle Assessment of Aquaculture Systems: Does Burden Shifting Occur with an Increase in Production Intensity?. Aquacultural Engineering, 102130.

The article appears as published, although style and formatting modifications have been made. Here a literature review is established regarding aquaculture systems environmental impacts, and opportunities to prevent burden shifting for aquaculture food production systems.

Authorship contribution statement

Ramin Ghamkhar: Designed Research, Performed Research, Analyzed Data, Wrote the Paper.

Suzanne E. Boxman: Designed Research, Performed Research, Analyzed Data, Wrote the Paper.

Kevan L. Main: Designed Research, Provided Feedback, Revised Paper.

Qiong Zhang: Designed Research, Provided Feedback, Revised Paper.

Maya A. Trotz: Designed Research, Provided Feedback, Revised Paper.

Andrea L. Hicks: Designed Research, Provided Feedback, Wrote the Paper.

2.1. Introduction

Finfish and other aquatic animals are critical to providing a high-value protein source and important micronutrients for much of the world. As production from capture fisheries remains stable (FAO, 2018), aquaculture's critical role in meeting increased demand for aquatic food products is driving researchers to assess the sustainability of the industry. In addition, consumers are becoming increasingly concerned with the environmental and ethical impacts of their food choices (Andersson, 2000). Considering aquaculture's major contribution to global food supplies and security, it is important to evaluate the current environmental impacts associated with aquaculture.

Life cycle assessment (LCA) is a tool used to quantify local, and global environmental impacts of systems and processes. It is considered a "cradle to grave" analysis, meaning that the assessment includes raw material extraction through the final disposal of all components (Curran, 2006). LCA has become a valuable tool used to evaluate a variety of systems, including biofuel production, wastewater treatment systems, agriculture, and aquaculture (Campbell, Beer, & Batten, 2011; De Vries & de Boer, 2010; Stokes & Horvath, 2006).

Prior LCA studies have looked at environmental impacts from fishing vessels and fleets, fish feed, and aquaculture systems. Avadí and Fréon (2013) reviewed 16 papers on LCAs of capture fisheries production. The review focused on differences in methodologies used to complete the LCAs. Reviews by Henriksson, Guinée, Kleijn, and de Snoo (2012) and Bohnes, Hauschild, Schlundt, and Laurent (2018) focused on differences in aquaculture LCA methodologies and looked at different types of aquaculture production systems from 12 and 65 studies, respectively. They found variability in the methodologies used and allocations made, and suggested that their needs to be a standardization of methodology and aquaculture specific impact categories. Variations in reporting methodological and data choices hinder direct comparison of different studies; however, important industry trends can still be seen by reviewing different LCA analyses of aquaculture.

Aquaculture systems vary in design and can be divided into two general categories linked to intensity of practice: extensive and intensive (Figure 1). Intensive aquaculture systems, such as recirculating aquaculture systems (RAS), in which 90 to 99 % of system water is recycled (Maddi Badiola, Mendiola, & Bostock, 2012), are commonly cited as a more sustainable option for aquaculture production due to localized reduction in water inputs and nutrient discharges. However, the high energy and material requirements for RAS, which can contribute to greater global impacts, such as global warming potential, are not usually included when discussing the sustainability of intensive systems. Alternatively, extensive systems often require fewer feed and energy inputs (Naylor et al., 2000; Wirza & Nazir, 2020). Extensive systems potentially have fewer global environmental impacts, although the open system boundaries can result in greater direct ecological impacts, such as degradation of water quality (Stickney, 1994).

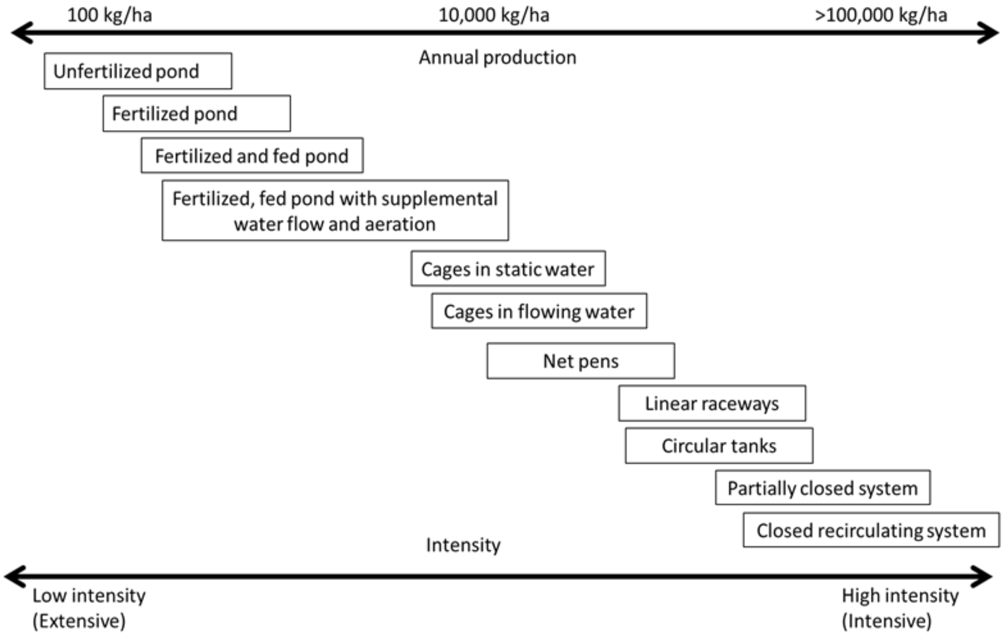

Figure 1. Continuum of aquaculture production methods (adapted (Stickney, 1994)).

Due to potential variation in environmental impact associated with aquaculture production methods, this review compares high input intensive systems to low input extensive systems. The aim of this review was to comparatively evaluate studies on intensive and extensive aquaculture systems, within a LCA framework, to develop a more complete picture of the environmental trade-offs incurred due to intensification of aquaculture systems.

2.2. Materials and Methods

Studies on aquaculture production systems were reviewed to compare differences in environmental impact. Papers were identified using web searches in the online database ScienceDirect and the internet search engine Google Scholar using combinations of the keywords: life cycle assessment, environmental impact, fisheries, aquaculture, recirculating aquaculture systems, and integrated aquaculture systems. Eighteen papers, that contained information on the pertinent aquaculture systems, were selected and discussed based on the following criteria: (1) Capture fisheries were neglected given the published review by (Avadí & Fréon, 2013); (2) Life cycle impact assessment were the primary aim of the studies; and (3) information on the nature of production system (intensive vs extensive) were clearly highlighted. A tabulated list of studies and important characteristics of each study is provided in Table 1.

Table 1. List of studies included in literature review and important characteristics of each study.

Study	Systems included	Location	Species	Functional unit	Impact assessment method[1]	FCRs	Infrastructure included	Integrated with other animals/plants
Aubin, Papatryphon, Van der Werf, and Chatzifotis	Flow through; sea cages; RAS	France, Greece	Rainbow trout; Sea-bass; Turbot	1 ton harvest ready live-weight fish	Papatryphon et al. (2004)	1.21, 1.77, 1.23	Yes	No
Aubin, Papatryphon, Van der Werf, Petit, and Morvan	RAS	France	Turbot	1 ton live fish weight	Papatryphon et al. (2004)	1.23	Yes	No
Nathan W Ayer and Tyedmers (2009)	Marine floating bag; land-based flow through; land-based RAS	Canada	Salmonids	1 ton harvest-ready live-weight fish	CML 2 Baseline 2000; CED v 1.03	N/R*	Yes	No
Efole Ewoukem et al. (2010)	Fish ponds integrated with pig manure, wheat bran, pig manure and crop by-products, or pig and chicken manure	Cameroon	Tilapia	1 ton fresh fish	CML 2 Baseline 2001; Aubin et al. (2009)	N/R*	Yes	Yes
Gronroos, Seppala, Silvenius, and Makinen (2006)	Net cage and land-based ponds	Finland	Rainbow trout	1 ton un-gutted rainbow trout after slaughtering	Individually calculated	1.255, 0.9, 1.53	No	No
Jerbi, Aubin, Garnaoui, Achour, and Kacem	Traditional raceway, Cascade raceway	Tunisia	Sea bass, sea bream	1 ton live fish weight	CML 2 Baseline 2000; Papatryphon et al. (2004)	1.8, 2.1	Yes	No
Mungkung et al. (2013)	Net cage	Indonesia	Carp; tilapia	1 ton fresh fish to market	CML 2 Baseline 2000; CED v 1.03	1.7, 2.1	Yes	Yes
Nathan Pelletier and Tyedmers (2010)	Lake and pond	Indonesia	Tilapia	1 ton live-weight tilapia	CML 2 Baseline 2000; CED V1.03; Pelletier and Tydemers (2010)	1.7	No	No

Phong, De Boer, and Udo (2011)	Fish ponds (high, medium, low intensity) integrated with rice fields or orchards	Vietnam	Fish	kilocalorie and kg per farm product	Individually calculated	N/R*	Not specified	Yes
d'Orbcastel, Blancheton, and Aubin (2009)	Flow through; low head RAS	France	Trout (various sp.), artic char	1 ton of fish	CML 2 Baseline 2001	1.1, 0.8	Yes	No
Samuel-Fitwi, Nagel, Meyer, Schroeder,	Extensive flow through; Intensive flow through; RAS	Denmark, Germany	Rainbow trout	1 ton live trout	CML 2 Baseline 2000	N/R*	No	No
Wilfart, Prudhomme, Blancheton, and Aubin (2013)	RAS; semi-intensive pond; extensive polyculture pond	France	Salmon; common carp; tench; roach; perch; sander; pike	1 ton live fish	CML 2 Baseline 2001; CED v 1.05	0.95 (resirculating system), 1.29, (extensive) 0.86 (semi-extensive)	Yes	No
M Badiola, Basurko, Gabiña, and Mendiola (2017)	Pilot scale RAS	Northern Spain	Atlantic cod	1 kg grown-out cod, before slaughtering	CML 2 Baseline 2000	1.57	No	No
Abdou, Aubin, Romdhane, Le Loc'h, and Lasram	Circular net-cage (sea-cage)	Tunisia	Seabass & Seabream	1 ton of fish at the fish farm gate	CML 2 Baseline 2000	1.88 (seabass) 1.85 (seabream)	Yes	No
Biermann and Geist (2019)	Pond aquaculture	Southern Germany	Common carp	1 kg of live carp at the farm gate	International Reference Life Cycle Data System (ILCD)	2	No	No
McGrath, Pelletier, and Tyedmers (2015)	Floating aquaculture (SWAS)	Canada	Chinook salmon	1 ton live-weight salmon	- ReCiPe 1.07 - CED 1.05 - Papatryphon, Petit,	1.459	Yes	No
Henriksson, Dickson, Allah, Al-Kenawy, and Phillips	Conventional aquaculture + management practices applied	Egypt	Tilapia	1 ton live tilapia at farm gate (mass & economic allocation)	- 5th IPCC assessment report - CML Baseline 2013	1.39- 1.82	No	Yes
Yacout, Soliman, and Yacout (2016)	concrete ponds (intensive & semi-intensive)	Egypt	Tilapia	1 ton live tilapia at farm gate	Eco-Invent database 2008	NR*	No	No

*NR: Not Reported

The ISO 14040 four step methodology (goal and scope, life cycle inventory, life cycle assessment, interpretation) was used as a framework to compare the aquaculture LCA studies (Temizel-Sekeryan, Wu, & Hicks, 2020). The review is focused on variation in environmental impact of different aquaculture systems; however, an analysis of the goal and scope, system boundary, functional unit, allocation, and impact assessment methods were necessary to establish a baseline and facilitate comparison of each study's results. Subsequently the selected papers were compared according to the system processes commonly considered within the system boundaries, which included feed, energy, and infrastructure. Similarly, the common impact categories of land use, water use, and eutrophication potential were selected for in-depth analysis.

2.3. Results

2.3.1. Goal and Scope

The goal and scope definition is the first step of an LCA. It should provide a clear statement of the study's purpose. Development of the scope is often comprised of an explanation of the system boundaries, functional unit, the impact assessment methodology, impact categories, and allocation used in the study. This step determines what information is included or excluded in the LCA and facilitates or hinders comparisons between studies.

The organization of this information varied in the studies reviewed. Some studies included it all in one goal and scope section (Aubin et al., 2009; Nathan W Ayer & Tyedmers, 2009; Phong et al., 2011), but most divided the goal and scope into additional sections (M Badiola et al., 2017; McGrath et al., 2015). Only a few studies included a clearly expressed goal within the goal and scope definition (Abdou et al., 2017; Henriksson et al., 2017; Jerbi et al., 2012; Samuel-Fitwi et al., 2013; Yacout et al., 2016). Many included a goal in the introduction (Aubin et al., 2009; Aubin et al., 2006; Nathan W Ayer & Tyedmers, 2009; Biermann & Geist, 2019; d'Orbcastel et al., 2009; Efole Ewoukem et al., 2010; Gronroos et al., 2006; Phong et al., 2011; Wilfart et al., 2013). In general, the goals of the reviewed studies were to quantify or evaluate the environmental impacts of the studied systems, while some included comparisons of different systems or operational scenarios (Biermann & Geist, 2019).

2.3.2. System Boundaries

The system boundaries define what processes are included in the LCA. In its most basic form, this includes all processes from cradle to grave (Figure 2, the system boundaries for cradle to farm-gate and cradle to grave are shown; the inclusion of dashed processes varies with study). System boundaries of food product studies often stop at farm-gate and do not include processing, retail, or household use (Henriksson et al., 2012). Most of the reviewed studies used a boundary of cradle to farm-gate (Abdou et al., 2017; M Badiola et al., 2017; Biermann & Geist, 2019; Henriksson et al., 2017; McGrath et al., 2015; Yacout et al., 2016). Aubin et al. (2009) and

Mungkung et al. (2013) only looked at hatchery to farm gate. Gronroos et al. (2006) used a system boundary that ended at delivery to additional processing or retailers and included packaging materials, production, and manufacture.

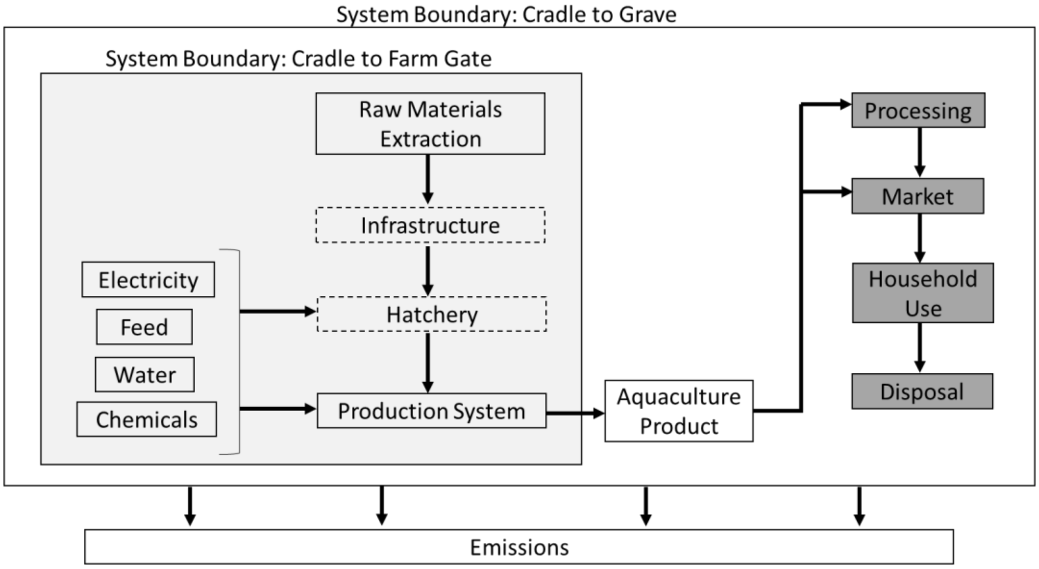

Figure 2. Generalized system diagram for aquaculture systems.

Within the defined boundary, each aquaculture system was broken into different processes. The classification of these components is up to the author's discretion and varied among the papers reviewed. Aquafeed, diet, or feed components were included in all studies. Energy carriers (e.g. electricity, natural gas, gasoline) or electricity production were also commonly reported as a separate process. If energy carriers were not included as a separate process they were included within other processes (Gronroos et al., 2006; Nathan Pelletier & Tyedmers, 2010). In the three studies where agriculture was integrated with aquaculture (Efole Ewoukem et al., 2010; Mungkung et al., 2013; Phong et al., 2011), energy was included in the system boundary but was not isolated as an individual process.

Across industries, infrastructure and capital goods have been excluded from LCAs based on the assumption that the impacts are relatively small (Frischknecht et al., 2007; Henriksson et al., 2012). Specifically within aquaculture, Nathan W Ayer and Tyedmers (2009) reported that infrastructure's impacts were negligible in salmon production. Based on the results of Nathan W Ayer and Tyedmers (2009), studies by Nathan Pelletier and Tyedmers (2010); Nathan Pelletier et al. (2009) excluded infrastructure in their LCAs. The studies that were more likely to include infrastructure as a process were those that evaluated either land-based RAS or flow-through systems. Samuel-Fitwi et al. (2013) looked at RAS and flow-through systems, but provided no justification for excluding infrastructure in an LCA. Most studies that looked at ponds or net cages did not include infrastructure except (Efole Ewoukem et al., 2010).

2.3.3. Functional Unit

LCA relates the environmental impact to the production system through the functional unit (FU). The FU quantifies the intended purpose of the production system. Comparisons between different systems are only possible if they have the same FU. Typically the FU is based on the primary product produced but can be refined to include temporal and quality criteria for a more complete description of the system function (Avadí & Fréon, 2013; Cooper, 2003).

The papers reviewed used similar functional units, in that they were mass quantities of fish. The amount of post-harvest processing, species, and quantity varied between papers. In general, all the FUs were variations on either 1 kg or 1 ton live-weight fish. Phong et al. (2011) studied an integrated agriculture-aquaculture system with multiple products and therefore used two FU: kilocalorie and kg per individual farm product.

2.3.4. Allocation

Many systems have multiple products, which poses a problem when estimating the environmental impact. The environmental impact is not necessarily equally divided between the multiple outputs or co-products. Material and energy flows attributed to co-products must be allocated in a systematic way (Henriksson et al., 2012). The ISO-Norm (2006) describes a three step hierarchy to address allocation issues: 1) avoid allocation through subdivision or system expansion, 2) use allocation based physical relationships, 3) use allocation based on another non-physical relationship.

Five papers used economic allocation to divide environmental impacts between co-products where necessary. In Nathan W Ayer and Tyedmers (2009) and Nathan Pelletier and Tyedmers (2010), the gross nutritional energy content was used to allocate environmental burdens. Allocation by gross nutritional energy content has been proposed as appropriate for seafood production because it incorporates the main function of aquaculture, chemical energy production in the form of food (Nathan Wayne Ayer, 2007). Nathan W Ayer and Tyedmers (2009) also used system expansion to account for recovered fish waste in a RAS. To account for the use of fish waste as an organic fertilizer, an offset of an equivalent amount of chemical fertilizer was applied. In Gronroos et al. (2006), allocation was avoided by using whole fish as the functional unit to prevent allocation issues with co-products during processing.

2.3.5. Impact Assessment Methods

Life cycle impact assessment involves selecting impact categories and assigning associated characterization factors to the materials and energy inputs and outputs (Avadí & Fréon, 2013; Wu, Zhou, Temizel-Sekeryan, Ghamkhar, & Hicks, 2020). A standardized method is often used to apply the characterization factors to the life cycle inventory results; however, some methods are calculated independently (Avadí & Fréon, 2013). A wide range of impact categories and characterization methods have been used for aquaculture studies. The dissimilarity of impact categories used can impede comparison between studies, similar to difficulties with different system boundaries or functional units.

In total, twenty three different impact categories were used (Table 2). The CML baseline method was the only standardized method used to calculate common impact categories, such as eutrophication potential, acidification potential, and global warming potential. Studies that did not use the CML baseline method or had additional impact categories, used independent methods for characterization.

Table 2. Impact categories used in reviewed LCA studies with reporting units.

Impact	AD*	GWP*	CC*	HTP*	MTP*	AP*	EP*	CED *	EU *	NREU*	TCED *	FEU *	NPPU *	LC*	LU*	SU*	LO*	WU/ WD*	Other **
Unit	kg Sb eq	kg CO_2 eq	kg CO_2 eq	kg 1,4-DB eq	kg 1,4-DB eq	kg SO_2 eq	kg PO_4 eq	MJ	MJ	GJ and MJ	GJ	kJ	kg C	m^2a or m^2yr^{-1}	m^2/ yr	m^2	m^2 /yr	m^3	N/A
(Aubin et al., 2009)			x			x	x		x				x					x	
(Aubin et al., 2006)		x				x	x			x (MJ)			x						
(Ayer and Tyedmers, 2009)	x	x		x	x	x	x	x											
(Efole Ewoukem et al., 2010)						x	x			x (GJ)			x		x			x	
(Gronroos et al., 2006)			x			x	x												
(Jerbi et al., 2012)		x				x	x		x				x			x (m^2/ yr)		x	
(Mungkung et al., 2013)			x			x	x		x				x				x	x	
(Pelletier and Tyedmers, 2010)		x				x	x	x					x						
(Phong et al., 2011)			x			x	x (NO_3 eq)					x			x (m^2)				
(d'Orbcastel et al., 2009)		x				x	x		x				x			x		x	
(Samuel-Fitwi et al., 2013)		x				x	x							x				x	
(Wilfart et al., 2013)			x			x	x				x		x	x				x	
(Badiola et al., 2017)	x	x				x	x		x										
(Abdou et al., 2017)		x				x	x				x		x				x		x
(Biermann and Geist, 2019)			x	x		x	x												x
(McGrath et al., 2015)		x				x	x	x					x						
(Henriksson et al., 2017)		x				x	x		x						x			x	
(Yacout et al., 2016)		x				x	x	x										x	
Sum	2	11	6	2	1	18	18	4	6	2	2	1	10	2	3	2	2	9	2

* AD: Abiotic Depletion; GWP: Global Warming Potential; CC: Climate Change; HTP: Human Toxicity Potential; MTP: Marine Toxicity Potential; AP: Acidification Potential; EP: Eutrophication Potential; CED: Cumulative Energy Demand; EU: Energy Use; NREU: Non Renewable Energy Use; TCED: Total Cumulative Energy Demand; FEU: Fossil Energy Use; NPPU: Net Primary Production Use; LC: Land Competition; LU: Land Use; SU: Surface Use; LO: Land Occupation; WU: Water Use; WD: Water Dependence.

** Other: Impact categories that are either ad-hoc basis or case-specific.

All studies included eutrophication and acidification potentials. For the characterization of eutrophication potential, Gronroos et al. (2006) individually considered eutrophication of aquatic and terrestrial systems, and used characterization factors specific to Finland for each distinguished impact factor (as opposed to using standardized eutrophication impact characterization and assessment methods). A measure of kg CO_2 equivalents was included in all the studies termed either greenhouse gas emissions or climate change. Energy use was considered in all but two of the investigated papers; five different terms were used and three different units.

The above impact categories are all measures of abiotic (non-living) resource use; however, in food production, biotic (living) resources are also consumed. Net primary production (NPP) can be used as a quantifiable measure of biotic resource use. The calculation of NPP use (NPPU) is based on the principle that plants convert sunlight into chemical energy and store it as carbon complexes. These carbon complexes move between trophic levels losing efficiency as carbon is transferred to higher trophic levels. NPP is a finite resource, using it as an impact category can help identify areas of inefficient resource allocation and can be used to improve the ecological efficiency of aquaculture (N Pelletier & Tyedmers, 2007). NPPU measured as kg C was used as a characterization factor in eight of the papers reviewed. Most papers used the methodology described in (Papatryphon et al., 2004). Only Nathan Pelletier and Tyedmers (2010) calculated biotic resource use with methods described in Pauly and Christensen (1995) (narrowly described later by Ghamkhar and Hicks (2020)).

In seven of the reviewed papers, land or surface use was used as an impact category. Land use encompasses the alteration of land directly through the removal of natural landscape due to deforestation, agricultural practices, or construction of impervious surfaces (Brentrup, Küsters, Lammel, & Kuhlmann, 2002). The assumption is that land should be conserved and excessive loss of land due to human development, has negative impacts on the environment (Brentrup et al., 2002). Land use or land use occupation is typically measured as an area over time, annual cubic meters (m^2a) or cubic meters per year (m^2yr^{-1}) (Mattila et al., 2011). Each paper independently calculated land use and accounted for surface area occupied by crops for feed production and area occupied by physical aquaculture systems in m^2, m^2a, or m^2/year.

Land use is one method to connect natural resources with aquaculture. water use or water dependence are also measures of natural resource depletion. In aquaculture, water use is of particular importance because some production systems, like flow-through systems, are criticized for high volumes of water use, while others like RAS are commended for low water use. Incorporating this impact category, can provide information about possible burden shifting of decreased water use. Nine of the reviewed studies incorporated water use/water dependence as an impact category measuring m^3 of water flowing into production systems.

2.3.6. Impact Assessment Results and Interpretation

Interpreting the results from the impact assessment is the final step of a LCA. The purpose of the interpretation step is to translate the results from the impact assessment into general conclusions about the type of environmental impact (global warming, eutrophication, etc.) and the system processes that contributed greatest (feed, energy, etc.). In the sections below, the results from three processes (feed, energy, and infrastructure) and three impact categories (land use, water use, and eutrophication) are discussed in depth.

2.3.6.1. Feeds

In the reviewed papers that compared different types of aquaculture systems in relation to feed, feed typically had the greatest environmental impact on NPPU and energy use (EU). In d'Orbcastel et al. (2009), a comparison between a RAS and a flow-through system for the production of trout showed that feed contributed greatest to NPPU (21,432 to 28,126 kg C) and energy (17,746 to 23,289 MJ). A sensitivity analysis on the feed conversion ratio (FCR) showed a reduction in NPPU and energy use could be achieved if the FCR of the RAS was decreased from 1.1 to 0.8. While the suggested 0.8 FCR was based on an experimental RAS, this level of efficiency is achievable in RAS producing various trout (Buric, Bláhovec, & Kouril, 2014; d'Orbcastel et al., 2009), and salmon (Carter, Bransden, Lewis, & Nichols, 2003; John Davidson et al., 2016; Ghamkhar & Hicks, 2020) species.

Similar results from a reduction in FCR were found in Jerbi et al. (2012) comparing two types of flow-through systems. Feed contributed approximately 40,000 kg C, which could be due to the higher FCRs of 1.89 and 2.11. Estimates of energy use from feed for the systems of Jerbi et al. (2012) ranged from 29,000 MJ to 33,412 MJ (system total energy use ranged from 170,000 to 280,000 MJ), and these were also likely higher than in d'Orbcastel et al. (2009) due to the higher FCRs. Aubin et al. (2009) compared a trout flow-through system (FCR=1.21), sea-bass cages (FCR=1.77), and a turbot RAS (FCR=1.23). Similar as above, feed production contributed greatest to NPPU and EU. The NPPU was 62,200, 71,400, and 60,900 kg C for the flow-through, cage, and RAS respectively. The values are similar to those found in Jerbi et al. (2012), but greater than those found in d'Orbcastel et al. (2009) possibly due to the variations in system boundaries despite similar FCRs.

Abdou et al. (2017) compared the environmental impacts of seabass (FCR=1.88) and seabream (FCR=1.85) production in a sea-cage aquaculture farm. Regardless of the system output, feed production proposed the greatest impact contribution to NPPU (>99%) and cumulative energy demand (71-79 %).

McGrath et al. (2015) evaluated the environmental impacts of salmon production (FCR=1.459), using a novel closed-containment aquaculture technology. In consistency with other studies, feed production contributed the greatest to NPPU (aka Biotic Resource Use - BRU, unit mass of C eq, 100%). However, the contribution of feed production to energy use was slightly lower than on-site energy use (39.7 % vs. 42.1 %). The NPPU was 1,429 Mg C and the cumulative energy use was 36,324 MJ for feed production. Figure 3 provides a conceptual illustration of the general correlation among FCRs versus NPPUs and EUs associated with food production using a regression analysis. Despite the fact that the plotted trends pose a relatively low regression (R^2) due to allocation differences across studies as well as limited data availability, there was general upward trend in associated environmental impacts with an increase in FCRs.

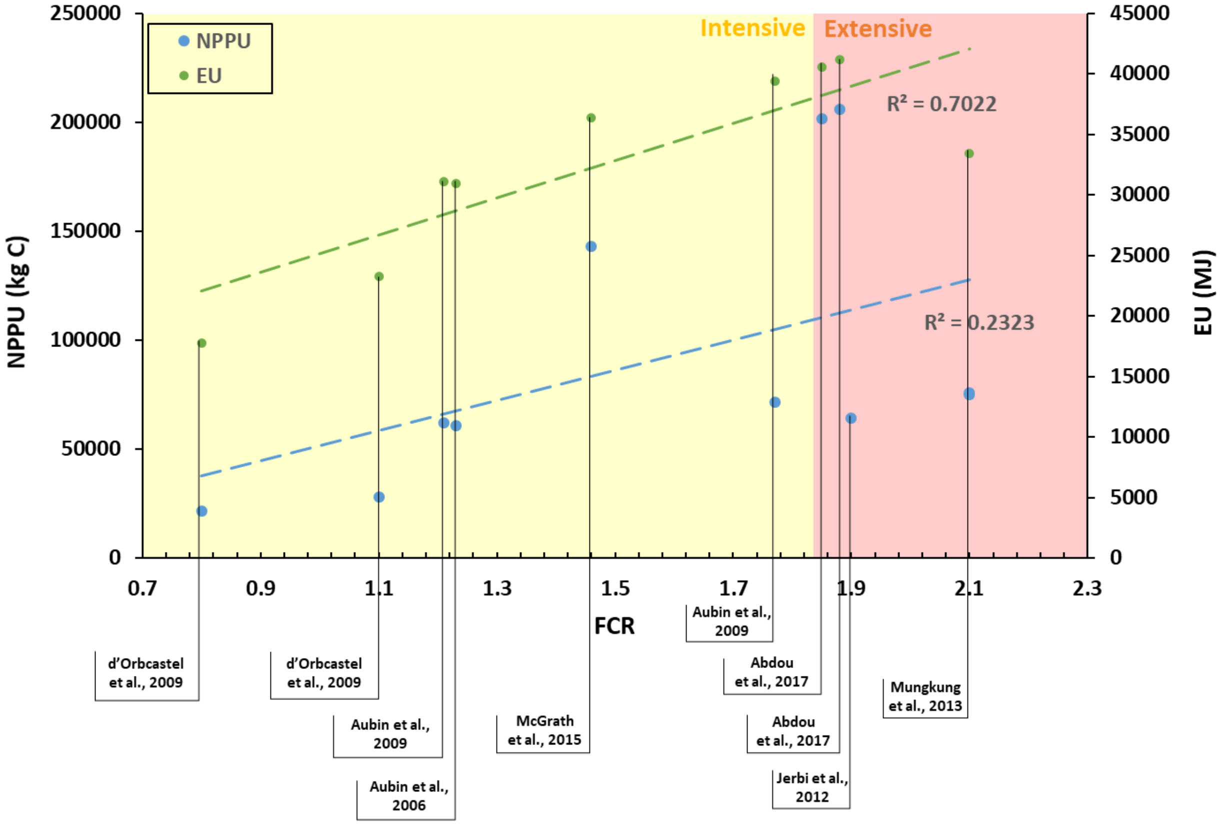

Figure 3. Net Primary Production Use (NPPU, left vertical axis) and Energy use (EU, right vertical axis) among investigated studies with various reported feed conversion ratios (FCR, horizontal axis).

The environmental impacts of feed can also change with intensity. In Samuel-Fitwi et al. (2013), three different system intensities were explored (extensive flow-through, intensive flow-through, and intensive RAS, EU were not incorporated). Impacts from feed decreased with increasing intensity for all investigated impact factors due to improved FCRs. Yacout et al. (2016) compared the environmental impacts of tilapia production in intensive and semi-intensive farms. Their assessment revealed that the production of tilapia in intensive farming has less impacts in global warming, acidification, and cumulative energy demand (despite higher impacts in eutrophication for intensive animal production, BRU and BRU categories were not incorporated).

As intensity increases, FCRs typically improve (M. Hasan & Soto, 2017) (Figure 3), which results in overall decreased environmental impact, as shown with the sensitivity analysis on FCRs in d'Orbcastel et al. (2009). Mungkung et al. (2013) considered two net-cage systems with an intensive and semi-intensive stocking density. The systems were integrated such that they produced two species simultaneously. In the intensive, high density system the NPPU and energy use were 14,205 kg C and 28,645 MJ, respectively. These values were lower than in the semi-intensive, lower density system, which had an NPPU and energy use of 16,462 kg C and 32,945

MJ, respectively. Mungkung et al. (2013) concluded that the cause of this difference was due to the greater feed efficiency (i.e. lower FCR) in the intensive system.

In extensive systems, the relative contribution of feed is decreased because fertilizer, often in the form of animal manure, is added to increase primary production of algae and microorganisms on which the fish feed. Wilfart et al. (2013) looked at RAS and pond systems with two levels of intensity. The contribution of feed to NPPU was 333 kg C to 744 kg C because a lower quantity of the feed came from harvesting higher trophic level fishery resources.

Finally, it is important to mention that the implementation of FCR reduction strategies, regardless of feeding components, to mitigate the environmental impacts is not a coherent approach. Gronroos et al. (2006) looked at variations in feed, and found that improving the FCRs decreases the impacts of feed for all categories. However, this impact mitigation is attributed to changes in the feed composition (such as increasing the soy content). In Nathan Pelletier and Tyedmers (2010), crop and fisheries derived tilapia feeds were evaluated. The results from this assessment showed that the greatest contribution to NPPU was fish meal and fish oil used in pelleted feed. For example, fish oil uses over 40 times more kg C than palm oil. Cumulative energy demand was also greater from the fisheries derived components, however the margin was smaller. Fish oil was associated with 33,000 MJ and palm oil 4,580 MJ.

2.3.6.2. Energy

Energy was used as a system process in several of the reviewed papers and was typically reported as either electricity or energy carriers. In papers that did not consider energy directly as a process, the impact category cumulative energy demand or energy use was used to draw conclusions about the aquaculture system’s energy consumption and associated environmental impacts.

Intensive flow-through systems and RAS require large quantities of electricity for operation. When comparing flow-through systems and RAS, RAS typically have higher energy requirements due to the pumping requirements for water recirculation. In Nathan W Ayer and Tyedmers (2009), electricity for the RAS had an energy demand of 291,000 MJ compared with a demand of 70,100 MJ for the flow-through system. The impacts of electricity are also seen in global warming potential. The RAS had a global warming potential of 23,700 kg CO_2 eq and the flow-through had a global warming potential of 1,020 kg CO_2 eq associated with electricity. Other studies have found similar trends for energy in RAS and flow-through systems. Aubin et al. (2009) considered energy carriers as a process and compared three production systems, a cage system, flow-through system, and RAS. The energy use increased with higher on-farm energy consumption. The energy use for each system was 9,191 MJ, 37,132 MJ, and 290,985 MJ for the cage, flow-through, and RAS, respectively. The global warming potential followed the same trend and was 163 kg CO_2 eq, 406 kg CO_2 eq, and 3670 kg CO_2 eq for the cage, flow-through, and RAS, respectively. The calculated global warming potential in Aubin et al. (2009) was low compared to the RAS in Nathan W Ayer and Tyedmers (2009) despite similar energy use values because the latter evaluated system was located in France, where a higher proportion of electricity is produced by nuclear power plants. A sensitivity analysis in Nathan W Ayer and Tyedmers (2009) illustrated the importance of the type of electricity generation. When the energy mix was varied to include less coal-based production and more hydroelectricity, the global warming potential decreased from 23,700 kg CO_2 eq to 10,300 kg CO_2 eq. In M Badiola et al. (2017) two electricity scenarios (scenario 1: 100% from non-renewable source, and scenario 2: 50% from no-renewable – 50% from renewable source) were evaluated to assess the environmental impacts of a RAS. In the scenario that 50% of the electricity were provided from a renewable source (biogas from agricultural plants), global warming potential decreased from 21.64 to 14.74 kg CO_2 eq, based on average electricity consumption.

The source of electricity is not the only factor that impacts the energy process. In Wilfart et al. (2013), a turbot RAS required more energy (250,010 MJ), due to water heating and cooling requirements, than a salmon RAS (55,530 MJ). This highlights the importance of production type and specifications in energy consumption and associated impacts (Ghamkhar, Hartleb, Wu, & Hicks, 2020). The global warming potential followed the same trends. The turbot RAS had a global warming potential of 3,670 kg CO_2 eq and the salmon RAS had a global warming potential of 417 kg CO_2 eq. A study comparing two flow-through systems also concluded that operational decisions influence environmental impacts (Jerbi et al., 2012). The flow-through systems with a cascade raceway had greater electricity use due to greater pumping requirements. The LCA results showed a higher total global warming potential of 17,500 kg CO_2 eq in the cascade raceway, with electricity contributing greatest to the global warming potential. d’Orbcastel et al. (2009) also evaluated different operational characteristics of aquaculture systems. When two different pumping scenarios were considered for flow-through systems, the high pumping scenario had a greater energy use and global warming potential.

Extensive systems have much lower energy requirements than the intensive systems discussed above. In Phong et al. (2011) electricity was included in the LCA, but not directly as a process. The contribution to impact categories was divided into on-farm and off-farm use. For the impact category of energy use, most of the use was attributed to off-farm activities, which includes inorganic fertilizer production, rice co-products, and feed. Since this study considered integrated agriculture and aquaculture, the authors also looked at the contribution of farm products to the impact categories. The on-farm energy use for pigs and fish were similar at 314 kJ/kg and 353 kJ/kg, respectively, and poultry was higher at 583 kJ/kg. Mungkung et al. (2013) looked at extensive pond systems that produced multiple fish products. Energy was not considered directly as a process, but the impact category of energy use was used. Similar to Phong, DeBoer, and Udo (2011), feed contributed most to energy use; the contribution of farm operation was negligible. Nathan Pelletier and Tyedmers (2010) considered the process of farm energy use for the pond and lake systems studied. The lake systems did not require aeration. As such, they had low energy use and less of the global warming potential was due to farm energy use. In contrast, the pond systems required more electricity for aeration and had higher energy use and global warming potential.

2.3.6.3. Infrastructure

In addition to energy, infrastructure is another factor that distinguishes intensive and extensive aquaculture systems. Intensive cage systems, flow-through systems, and RAS all have greater material requirements than extensive pond systems. In an LCA these material inputs are occasionally considered, but more frequently they are considered negligible and are excluded from the life cycle inventory (Avadí & Fréon, 2013; Ghamkhar, Hartleb, et al., 2020).

Nathan W Ayer and Tyedmers (2009) included infrastructure and provided tables showing their inventory data. Of the four systems compared, the RAS and net-pen systems typically had high impacts from infrastructure. Most of the impacts from infrastructure were seen in the marine toxicity potential and the second greatest impact was to cumulative energy demand/energy use. Focusing on the marine toxicity potential and cumulative energy demand/energy use impact categories, the impacts from infrastructure were consistently much lower than the impacts of electricity or feed production. For example, in the RAS that had the highest impact to marine toxicity potential, infrastructure only contributed 0.13%. In contrast, electricity production contributed 93% of the marine toxicity potential.

Other studies that included infrastructure also reported that it contributed to less than 13% of environmental impact for all impact categories included. Aubin et al. (2009) considered infrastructure impacts on three types of aquaculture systems. No trends were observed between production systems. The greatest impacts from infrastructure were to cumulative energy demand and climate change, but they were all less than 13%. The other papers reviewed which considered infrastructure were Abdou et al. (2017); d'Orbcastel et al. (2009); Jerbi et al. (2012); Mungkung et al. (2013); Wilfart et al. (2013), and McGrath et al. (2015).

2.3.6.4. Land Use

Land use (LU), land competition (LC), or surface use (SU) were impact categories considered in nine of the papers reviewed. Each term is associated with a different characterization method, since methods for inclusion of land use in LCAs are still debated (Mattila et al., 2011). Most of the papers reviewed used the method outlined in the Handbook on Life Cycle Assessment by Guinée (2002) developed by the Center for Environmental Studies, University of Leiden.

Collectively the results for the land use characterization factor, regardless of methodology or units used, indicated that feed production had the greatest impact on land use. Jerbi et al. (2012) investigated surface use measured in m^2/yr and found that the tank surface area occupied by a flow-through system was negligible when compared to the surface area associated with fish feed. d'Orbcastel et al. (2009) looked at surface use in m^2 and also found feed contributed more to surface than any other process. Feed contributed 2,097 to 2,736 m^2 of surface use, while other processes contributed 0.0-0.2 m^2. When FCR was decreased, the authors saw an associated decrease in surface use. At an FCR of 1.1, surface use from feed was 2,752 m^2. When FCR was decreased to 0.8, surface use decreased to 2,097 m^2. Two pumping scenarios, a high and a low scenario, were also considered in this study. The changes in pumping requirements did not impact surface area, further indicating the importance of feed to surface use. In Abdou et al. (2017), feed contributed to 98.7% (1351.15 m^2/year) and 98.1% (1311.38 m^2/year) of the land occupation per ton of seabream and seabass produced respectively.

A comparison of three different production system intensities in Samuel-Fitwi et al. (2013) found that electricity sources can also impact land competition. For the RAS studied in Samuel-Fitwi et al. (2013), feed contributed to 62% of land competition, and electricity contributed to 38% of land competition. When electricity generation was changed to include wind power in a sensitivity analysis, the total land competition dropped to 928 m^2a or about 37% less. Due to the higher energy requirements, RAS had the greatest impact on land competition compared to both intensive and extensive flow-through systems. Moreover, due to the higher feed requirements in the extensive system, it posed higher land competition compared to the intensive system.

When compared to extensive systems, RAS had the lowest contribution to land competition in m^2yr, the extensive pond was second, and the semi-extensive pond was greatest (Wilfart et al., 2013). Instead of feed production, the on-farm fish production contributed to most of the land competition. Similar results were found in Efole Ewoukem et al. (2010), which compared the intensive flow-through system from Aubin et al. (2009) to several Cameroonian pond systems. The integrated pig and fish pond system (4,369 m^2/year) had greater land use impacts than the flow-through system (2,351 m^2/year). When compared to the other extensive pond systems in Cameroon, the impacts to land use decreased with decreasing productivity. The extensive systems studied in Phong et al. (2011) did not find land use significantly impacted by any of the processes included. When assessed on an m^2/kcal basis, all land use impacts were 0.023 m^2/kcal with no differences between on and off farm use.

2.3.6.5. Water Use

Similar to land use, water use (WU) is a relatively new development in LCA characterization factors. It is important to consider in aquaculture production because one of the main benefits to developing RAS is the reduction in water use compared with extensive and semi-intensive production systems (Bohnes et al., 2018). In the papers reviewed, water use and water dependence (WD) was calculated based on direct water use, specifically the quantity of water flowing into the production systems. Henriksson et al. (2017); Mungkung et al. (2013) were exceptions and also indicated that the quantity of water used for crop irrigation was included in the water use. None of the papers reviewed considered indirect water use (the water used in the processing of underlying and upstream production chains, such as in feed production and electricity generation).

Aubin et al. (2009) found an increase in water use efficiency with increasing intensity. The RAS was the most water efficient, using 4.8 m^3, the cages used 52.6 m^3, and least efficient was the flow-through system, which used 48,782.2 m^3. Yacout et al. (2016) found similar results. Water use for intensive tilapia production was 200 m^3, while it was 35,700 m^3 for semi-intensive tilapia production. When feed and pumping requirements were varied in d'Orbcastel et al. (2009), there was no change in the water use. A comparison of flow-through and RAS showed a 93% reduction in water use. In Jerbi et al. (2012), the cascaded flow-through systems had a water dependence of 396,000 m^3 compared to only 190,000 m^3 in the traditional flow-through system. A comparison of two types of flow-through systems in Samuel-Fitwi et al. (2013), showed that the intensive flow-through system used only 1% of the water required in the extensive flow-through system. A RAS was also included in this comparison and it had 0% water use relative to the two flow-through systems.

In extensive systems, water use will vary with size of the ponds and production practices. The comparison of four pond systems in Cameroon showed that despite similarly sized ponds the water dependence varied and was not related to yield (Efole Ewoukem et al., 2010). The integrated pig and fish system had a water dependence of 16,900 m^3, whereas the pond fertilized with pig manure and crop by-products had a water dependence of 51,000 m^3 (i.e. 101.8% increase). In Wilfart et al. (2013), water dependence was related to the pond surface area. The extensive pond in this study had the greatest water dependence of more than 41,000 m^3, the semi-extensive pond had a water dependence of 7,500 m^3, and the RAS had a water dependence of 2,500 m^3. Mungkung et al. (2013) and Henriksson et al. (2017) were the only authors to consider additional sources of water dependence. In Mungkung et al. (2013), irrigation for agriculture was included in particular water for rice production. When agricultural water dependence was considered, feed production contributed greatest to water dependence (71%). High and low stocking density farming practices were considered. The low stocking density system had a higher water dependence of 1,121 m^3 compared to 877 m^3 in the high stocking density system. In Henriksson et al. (2017), Irrigation water on agricultural fields accounted for 7–12% of the overall freshwater consumption, which represented the second largest consumer of freshwater.

The papers reviewed consistently show RAS to have lower direct water requirements and flow-through systems to have high water requirements. The extensive pond systems will vary with farming practices and pond age (Efole Ewoukem et al., 2010). Extensive pond systems can have water use similar to a flow-through system, while others might be more conservative and have lower water requirements. However, even under the conservative water use conditions, the impact will still be approximately 500 times greater than RAS.

2.3.6.6. Eutrophication Potential

Eutrophication potential is based on nutrients, particularly nitrogen and phosphorous, emitted to environment. It is the one impact category that was included in all the papers reviewed. Like water use, the potential reduction in eutrophication potential is considered an advantage to RAS.

Several papers demonstrated lower eutrophication potential in RAS compared to flow-through or other production systems (Philis et al., 2019). Nathan W Ayer and Tyedmers (2009), which compared four production systems, found RAS to have the lowest eutrophication potential. The resulting eutrophication was predominately attributed to feed and electricity processes. In the other systems, eutrophication was predominately due to grow-out emissions (production of juvenile to market size fish, as compared to smolt production, fuel use, and feed production). In the sensitivity analysis, changing the electricity mix to incorporate more renewables reduced the eutrophication potential of the RAS from 20.1 kg PO_4 eq to 11.6 kg PO_4 eq (i.e. by 42.3%). Samuel-Fitwi et al. (2013) had similar results when comparing the extensive flow-through system, the intensive flow-through system, and the RAS, which had eutrophication potentials of 60.36 kg PO_4 eq, 60.03 kg PO_4 eq, and 4.04 kg PO_4 eq, respectively. In the flow-through systems, most of the eutrophication potential was due to fish production processes and in the RAS it was mainly due to electricity and feed processes. When the electricity was produced from wind power, the eutrophication potential for the RAS decreased by about half. M Badiola et al. (2017) integrated energy audits in LCA of RASs with analogous results. In the scenario that 50% of the electricity were provided from a renewable source (biogas from agricultural plants), eutrophication potential decreased from 0.04 to 0.02 kg PO_4 eq (i.e. 50% decrease), based on average electricity consumption.

Reduced water discharges in RAS due to recirculation contribute to the lower eutrophication potential, but does not guarantee a RAS will have a low eutrophication potential. In Aubin et al. (2009), the differences between the flow-through system and RAS were reversed. The flow-through and RAS had eutrophication potentials of 66 kg PO_4 eq and 77 kg PO_4 eq, respectively. The higher eutrophication potential of the RAS was due to a higher protein content in the feed of 55% compared to 45% in the flow-through system. In d’Orbcastel et al. (2009) a flow-through system was also compared to a RAS. The eutrophication potential was reduced by 26-38% in the RAS. The higher percent reduction was due to a lower FCR.

The eutrophication potential of a RAS will also vary depending on the facility. Wilfart et al. (2013) compared a RAS producing salmon and the turbot RAS studied in Aubin et al. (2009). The salmon producing RAS had a eutrophication potential of 34 kg PO_4 eq and the turbot RAS had an eutrophication potential of 77 kg PO_4 eq. The difference could be attributed to the higher energy use in the turbot facility, from heating and cooling the water. When the salmon RAS was compared to an extensive and semi-extensive pond system, the pond systems had lower eutrophication potentials than the RAS. The authors suggested that the lower emissions in the pond systems were due to internal nutrient cycling within the ponds which was not present in the

RAS. Similar results reported by Yacout et al. (2016), comparing intensive and semi intensive tilapia production systems. Intensive production resulted in 14.1 kg PO_4 eq, while semi-intensive production resulted in 6.3 kg PO_4 eq (55% less). The higher eutrophication impact in the intensive system were attributed to the intensive animal production in the aquaculture system.

In extensive systems, the eutrophication potential will depend on farm management practices. In Mungkung et al. (2013), the extensive pond and cage system that used feed more efficiently had a lower eutrophication potential. In Gronroos et al. (2006), the eutrophication potential was divided into aquatic and terrestrial based impacts and aquatic eutrophication was always greater than terrestrial eutrophication. In Biermann and Geist (2019), the eutrophication potential was divided in to terrestrial, freshwater, and marine eutrophication. Their evaluation, however, resulted in higher terrestrial eutrophication compared to marine eutrophication (for both conventional and organic carp production scenarios). While fish production generally contributes greatest to eutrophication potential, feed type also affects the overall emission-based environmental impacts. Decreasing the FCR can reduce the eutrophication potential as seen in Gronroos et al. (2006) and Mungkung et al. (2013). Over-fertilization of pond systems will also result in a high eutrophication potential (Efole Ewoukem et al., 2010). The eutrophication potential of the Cameroonian ponds ranged from 157 kg PO_4 eq to 908 kg PO_4 eq. These values are at least double the trout flow-through system, which had an eutrophication potential of 66 kg PO_4 eq. While pond systems have reductions in some global environmental impacts, locally they contribute to greater eutrophication potentials without the benefit of increased yields as in intensive systems.

2.3.7. Monetary Valuation of Intensive vs. Extensive Production Strategies

To compare the overall favorability of increasing production intensity as a strategy to mitigate the overall environmental impacts, a trade-off analysis based on the pertinent impact categories and their relative impact level can be performed. In an effort to provide a comparative trade-off analysis of global and local impacts among intensive and extensive farming systems, GWP and EP have been selected, among the plethora of relevant indexes, as the most commonly investigated impact categories regarding global and local environmental impacts (Table 2)(Curran, 2006). Quantified GWP and EP impacts for the investigated studies who evaluated both impact categories (along with reported FCRs and cradle-to-gate system boundary), have been extracted from the literature and illustrated in Figure 4.

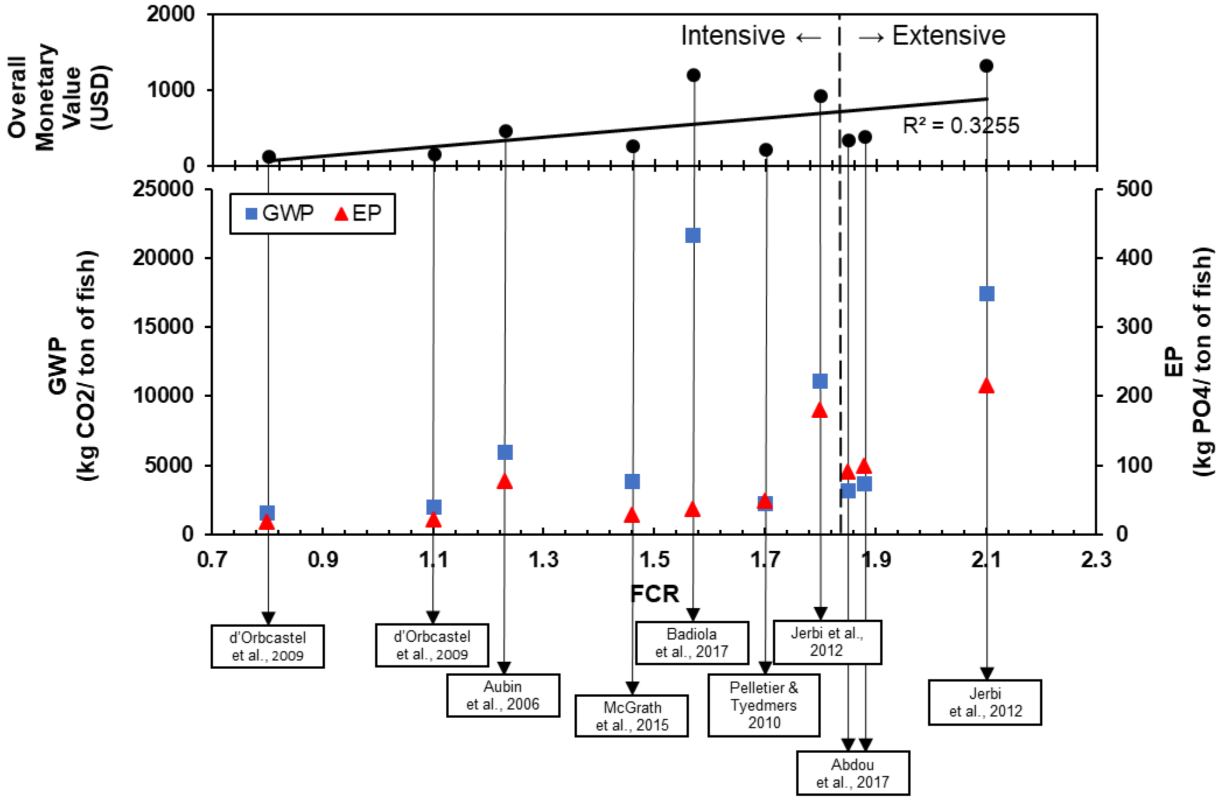

Figure 4. GWP and EP environmental impacts, and the associated overall monetary value of impacts based on FCRs. data are obtained from the investigated studies with reported GWP, EP, and FCR (10 datapoints).

An economic allocation of $52/ton of CO_2 for GWP (social cost of carbon) and $1.91/kg of PO_4 for EP have provided the opportunity to analyze and compare the impacts shift from extensive to intensive farming, considering an economic perspective. Social cost of carbon (for GWP) incorporates the long-term economic harms due to the net agricultural productivity changes, property damages from increased flood risk, human health, and changes in energy system cost (D. P. Council, 2013; Ghamkhar & Hicks, 2020). STEPWISE2006 (for EP) provides globally valid values to monetarize environmental impacts, using budget constraint method (Pizzol, Weidema, Brandão, & Osset, 2015; Weidema, 2009). An adjustment of 1.13 (to convert EUR2003 to USD 2003) times 1.41 (to incorporate inflation from 2003 to 2020) has been executed.

As shown in Figure 4, despite the fact that the plotted trends pose a relatively low regression (R^2) (due to allocation differences across studies as well as limited data availability), there is general downward trend in the associated overall monetary value of environmental impacts (GWP+EP) with a decrease in FCRs. This highlights the fact that shifting from extensive to intensive farming can be a potential approach to decrease the overall environmental impacts of aquafarming, considering both global and local indicators. However, it is important to mention that case-specific mitigation strategies (e.g. optimized heat in cold-weather setups, protein-rich feeds for carnivore species, etc.) needs to be investigated and applied to accomplish the overall improvement of farming environmental performance.

2.4. Discussion

In the first three steps of the LCA methodology, there are no specific patterns distinguishing intensive, semi-intensive, or extensive aquaculture production systems. The methodological choices are largely up to the author's discretion and intended goal. All the authors followed the guidelines developed by the International Standard Organization (ISO, 2008). The variation in functional units, system boundaries, allocation methods, and characterization factors does impede a direct comparison between LCA studies (Wu, Ghamkhar, Ashton, & Hicks, 2019). As mentioned in Avadí and Fréon (2013) more standardization for fisheries practices would aid future LCA fisheries research. The analysis of specific processes and impact categories did reveal a tendency for increased intensity to result in a shift from local to global impacts for some environmental burdens (e.g. decrease in acidification potential and increase in global warming potential).

The impact of aquaculture feeds is well known to be one of the main impediments to development of sustainable aquaculture, which is further supported by this review (Basto-Silva, Guerreiro, Oliva-Teles, & Neto, 2019; Bohnes & Laurent, 2019; Ghamkhar & Hicks, 2020). Both intensity level and FCR had clear impacts on the NPPU and cumulative energy demand/energy use of aquaculture systems (d'Orbcastel et al., 2009; Gronroos et al., 2006; Mungkung et al., 2013; Nathan Pelletier & Tyedmers, 2010). However, there are confounding effects to the impacts of feed between intensive and extensive systems. Extensive systems benefit from reduced feed requirements and therefore global environmental impacts due to supplemental primary production from fertilizers. The jump from extensive to intensive systems resulted in a large increase in global impacts from feed; however, more intensive systems can have also lower feed impacts due to improved efficiency and FCRs. Further improving FCRs is one way to reduce the impacts of feed. Although, at present, even with a low FCR, fish only incorporate 12% to 25% of the nutrients from feed into biomass (Lucas, Southgate, & Tucker, 2019). Alternatively, reducing the impacts from feed by improving the feed utilization of the whole system through production of a secondary species that used excess nutrients could increase the total system production and improve efficiency (Neori et al., 2004; Wu et al., 2019). These integrated multi-trophic aquaculture (IMTA) systems are suggested as a way to increase the environmental sustainability of RAS due to bio-mitigation of wastes and increase revenues (Barrington, Chopin, & Robinson, 2009; Ghamkhar, Hartleb, et al., 2020; Granada, 2015; Philis et al., 2019). The potential benefits of dual species production using the same amount of feed could also extend to reductions in electricity and fuel use due to greater production per unit of energy (Bibbiani, Fronte, Incrocci, & Campiotti, 2018; Bohnes & Laurent, 2019; Cederberg & Stadig, 2003).

As expected, the electricity and fuel use by intensive systems was consistently higher than in extensive systems. Intensive systems have greater pumping and aeration requirements resulting in greater global impacts of cumulative energy demand/energy use and global warming potential (M Badiola, Basurko, Piedrahita, Hundley, & Mendiola, 2018). In IMTA systems, greater production capacity can potentially moderate these impacts. This potential is illustrated by the reduced energy use at higher production densities with simultaneous production of two fish species in Mungkung et al. (2013). In addition, changing the electricity source can dramatically reduce the environmental impact of intensive RAS (Nathan W Ayer & Tyedmers, 2009; M Badiola et al., 2018; Samuel-Fitwi et al., 2013). Greater development and use of renewable energy sources will decrease the carbon emissions of intensive systems (Ghamkhar, Hartleb, et al., 2020; IEA, 1998; Proksch, Ianchenko, & Kotzen, 2019).

Unlike energy, the additional infrastructure attributed to intensive systems does not have a large environmental impact. In the studies that reported infrastructure as a separate process, the environmental impacts were negligible compared to the other impact contributors (i.e. <13%). It is common for infrastructure or capital goods to be excluded from a LCA. Buildings are considered to have long lifespans and after their contribution is divided by the building's total lifespan the environmental impact is insignificant (Morais & Delerue-Matos, 2010). Despite the frequent exclusion, Frischknecht et al. (2007) looked at the impacts of capital goods and found that they can have a significant impact on certain impact categories. As such, capital goods should not be excluded without consideration and proper justification for exclusion (Bohnes et al., 2018; Ghamkhar, Hartleb, et al., 2020). Several of the reviewed studies indicated that infrastructure did not contribute significantly; however, these studies did not include assumptions about infrastructure lifespan. Exclusion of infrastructure in future aquaculture studies should be considered carefully and will depend on anticipated lifespan of the production system (Ghamkhar, Hartleb, et al., 2020).

Similar to infrastructure, the impact category land use also had negligible impacts in intensive systems. The area occupied by tanks and water treatment equipment in intensive systems is much smaller than the area required to produce feed products. Extensive aquaculture requires more on-farm land use due to the increased area needed for pond construction and lower yields. When compared to other protein sources, intensive aquaculture production has fewer land use impacts on a kg live-weight basis. A comparison of pork, poultry, beef, and fish when normalized to m2/kg edible product indicated fish in RAS to have the lowest land use (Table 3).

Table 3. Comparison of land use (m^2) results from LCA studies.

Study	System	Functional Unit (FU)	m^2/FU	m^2/kg edible product*
Pork**				
Williams, Audsley, and Sandars (2006)	Heavier finishing	1 ton dead weight	6,900	9.8
Williams et al. (2006)	Indoor breeding	1 ton dead weight	7,300	10.3
Williams et al. (2006)	Outdoor breeding	1 ton dead weight	7,500	10.6
Williams et al. (2006)	Conventional	1 ton dead weight	7,400	10.5
Poultry**				
Williams et al. (2006)	Conventional	1 ton dead weight	6,400	8.0
Williams et al. (2006)	Free range	1 ton dead weight	7,300	11.9
Beef**				
Williams et al. (2006)	100% sucker	1 ton dead weight	38,500	49.2
Williams et al. (2006)	Lowland	1 ton dead weight	22,800	29.2
Williams et al. (2006)	Hill and upland	1 ton dead weight	24,100	30.8
Williams et al. (2006)	Non-organic	1 ton dead weight	23,000	29.4
Fish**				
Jerbi et al. (2012)	Cascade flow-through	1 ton live fish weight	4,940	9.9
Jerbi et al. (2012)	Traditional flow-through	1 ton live fish weight	4,260	8.5
d’Orbcastel et al. (2009)	RAS, FCR 0.8	1 ton fish	2,097	4.2
d’Orbcastel et al. (2009)	RAS, FCR 1.1	1 ton fish	2,752	5.5
Wilfart et al. (2013)	RAS	1 ton fish	740	1.5
Wilfart et al. (2013)	Semi-extensive pond	1 ton fish	30,897	61.8
Wilfart et al. (2013)	Extensive pond	1 ton fish	56,750	114

Abdou et al. (2017)	Sea-cage (intensive / seabass)	1 ton fish	1,336	2.6
Abdou et al. (2017)	Sea-cage (intensive / seabream)	1 ton fish	1,369	2.7
Henriksson et al. (2017)	Conventional (intensive / tilapia)	1 ton fish	1,199	2.2

*kg edible product for pork, poultry, and beef calculated based on information in De Vries and de Boer (2010); kg edible product for fish based on assumption of 0.5 kg edible product/ kg live weight (Iversen, 1996)

** Data on pork, poultry, and beef from (De Vries & de Boer, 2010). Data on fish based on studies in this review.

Similar to intensive systems, off-farm land use requirements of other protein sources are attributed to feed production (Thomassen, van Calker, Smits, Iepema, & de Boer, 2008). Poultry, beef, and pork rely on similar agricultural feed products as those used to supplement fish meal in aquaculture feeds (Ellingsen & Aanondsen, 2006). Changing the aquaculture feed composition to include more plant derived ingredients could increase the land use requirements of aquaculture production. It could also increase competition for land use with other protein sources due to reliance on the same ingredients (despite potential impact decrease in other categories such as NPPU). In contrast, extensive aquaculture systems require less supplemental feed and indirectly compete less for plant derived feed ingredients; however, extensive systems could compete directly with other protein sources due to the large on-farm area requirements.

Water use is a unique impact factor considered in several of the reviewed papers. Intensive RAS systems utilize water more efficiently and therefore had lower water use impacts than flow-through or extensive aquaculture systems. Of the papers reviewed, two studies accounted for agricultural irrigation (indirect use) and found irrigation contributed significantly to water use (Henriksson et al., 2017; Mungkung et al., 2013). The exclusion of irrigation for feed ingredients by studies on intensive aquaculture systems potentially ignores a large water requirement. Commercial feeds used in intensive systems with a high quantity of plant derived ingredients will have lower NPPU impacts at the risk of greater water use impacts. The agricultural industry is one of the largest users of fresh water resources and most of the grains produced go into animal feeds (Goodland, 1997). If aquaculture feeds incorporate more agriculturally produced plant ingredients, it could potentially increase the water use of those systems placing more stress on limited water supplies. To properly compare water use of an intensive RAS and extensive pond system the water use in feed production must be considered within the system's boundary.

Incorporation of the irrigation water for feed production could minimize difference in water use between intensive and extensive systems. For this reason, as with feed and energy, it could be beneficial to integrate aquaculture systems with additional products (Bibbiani et al., 2018; Wu et al., 2019). Increased production per m^3 of water could mitigate indirect agriculture-related water use.

While the assessment of water use in the reviewed papers is useful as a baseline comparison between systems, they are extremely simplified. The studies only consider direct quantity of water flowing into the system. As such, the assessments lack distinction between types of water used (blue, green, or grey), consumptive and non-consumptive uses, and spatially relevant scarcity (Ridoutt & Pfister, 2010, 2013). A new method to describe both consumptive and degradative water use, while incorporating an indicator of global water stress is developed for LCA (Ridoutt & Pfister, 2013). Future research on aquaculture should include this new method or even the commonly used Water Footprint Network method as described by (Hoekstra, Chapagain, Mekonnen, & Aldaya, 2011), which includes indirect water use to provide more robust measures of water use.

Despite possible limitations in the water use category, increased water efficiency resulted in lower eutrophication potentials. Extensive systems that rely on pond fertilization have greater direct emissions due to on-farm production. In addition to greater direct emissions, the lower yields in an extensive system resulted in a greater eutrophication potential per unit mass of ultimate product, compared to the highly productive intensive systems (Bibbiani et al., 2018; Bohnes et al., 2018; Thomassen et al., 2008). Furthermore, some extensive systems also supplement with commercial feeds thereby increasing indirect emissions from plant derived feed ingredients (Chary et al., 2020; Nathan Pelletier & Tyedmers, 2010). In contrast, intensive systems are the result of a historical focus on reducing local water quality and ecological impacts. The low eutrophication potential of RAS is evidence to support the success of this movement. Instead of direct emissions, eutrophication potential is largely due to the off-farm impacts of energy production and feed production. Therefore, further reductions in eutrophication potential will come from reducing the impacts of feed and energy with improved FCRs, alternative feed ingredients, and alternative energy sources, or the elimination of all waste discharge. Such zero-emission RAS are currently being developed that include IMTA or additional treatment systems (Chary et al., 2020; Van Rijn, 2013).

While zero-emission RAS, specifically IMTA, have great potential to reduce the environmental impact of aquaculture systems (Czyrnek-Delêtre, Rocca, Agostini, Giuntoli, & Murphy, 2017; Ghamkhar, Hartleb, et al., 2020; Ianchenko & Proksch, 2019; Proksch et al., 2019), future research is needed to quantitatively evaluate these new systems. It remains in question how the incorporation of additional products will change the environmental impact when evaluated through LCA. In addition, methods to address allocation in multi-output IMTA systems has yet to be studied. In this review, seven papers included allocation and of those only two applied the system expansion method. Considering the inevitable allocation issues in IMTA and its limited use in aquaculture studies, the use of system expansion to address allocation in both IMTA and aquaculture are potential research areas.

Future LCAs on zero-emission aquaculture systems, freshwater and marine, will be needed to clarify the advantages and disadvantages of multiple products and its associated water treatment in terms of environmental impact. Just as there was a possible burden shift moving from extensive to intensive aquaculture systems a more in-depth assessment of zero-emission systems may uncover trade-offs to integration.

2.5. Conclusion

A comparison of different production systems, with a focus on the differences between intensive land-based systems and extensive pond systems, showed an improvement of overall environmental performance, with a possibility of burden shifting when moving to more intensive aquaculture systems. Intensive systems are often considered to have fewer negative environmental impacts than extensive systems, specifically less water pollution and total water use. Exploration of these environmental impacts through the LCA lens provided support for these claims about intensive aquaculture. It also showed that other impacts, such as cumulative energy demand/energy use and NPPU, are greater. In areas where electricity is predominately supplied by fossil fuels, the greater energy requirements correspond with greater carbon emissions. Facilities located in areas, such as Europe, that have access to renewable energy sources benefit from a reduction in carbon emissions despite greater energy requirements. The future of intensive land-based aquaculture development in the United States, which does not have a strong renewable energy market, nor has it established a federal renewable energy policy to encourage such a market, is at a distinct disadvantage due to the lack of renewable energy sources.

In addition to greater access to renewable energy sources, development of sustainable fish feed and the improvement of feed conversion efficiencies will reduce the environmental impacts of aquaculture. Aquaculture feed is well known to have large biotic resource and energy requirements. While the movement from extensive to intensive aquaculture resulted in an improvement of FCRs, fish can only incorporate a certain percentage of the nutrients in feed. Alternative aquaculture systems, which improve the total nutrient uptake and increase total yields thereby reducing impacts through greater production per unit of feed, water, and energy, are needed to further reduce the impacts of aquaculture.

This review demonstrates that while intensive aquaculture systems have greatly reduced negative, local environmental impacts; many negative, global environmental impacts may still remain without applying case-specific mitigation strategies. The achievement of sustainable aquaculture production will likely come from both improved technologies and a careful balance between local and global environmental impacts through management of production intensities.

2.6. Acknowledgement

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3. Chapter 3: Life cycle assessment of a cold weather aquaponic food production system

This chapter was adapted from: Ghamkhar, R., Hartleb, C., Wu, F., & Hicks, A. (2020). Life cycle assessment of a cold weather aquaponic food production system. Journal of Cleaner Production, 244, 118767.

The article appears as published, although style and formatting modifications have been made. Here, life cycle assessment of a cold-weather aquaponic system is performed to (1) quantify year-round environmental impacts, (2) identify major contributors (hotspots), and (3) evaluate alternative scenarios that affect the ultimate environmental impacts of the aquaponic food production system.

Authorship contribution statement

Ramin Ghamkhar: Designed Research, Performed Research, Analyzed Data, Wrote the Paper.

Christopher Hartleb: Provided Life Cycle Inventory Data, Revised the Paper, Provided Feedback.

Fan Wu: Provided Feedback.

Andrea L. Hicks: Designed Research, Provided Feedback, Wrote the Paper.

3.1. Introduction

It is predicted that the world population will rise from 7.55 billion people in 2017 to 11.18 billion by 2100 (Unies, 2017). Due to human population expansion, there will be a consequent increase in the world's food demand (FAO, 2009). Ecosystem degradation, due to necessitated intensive agricultural practices to feed an ever-growing population, is of great public and environmental concern. While at the same time, the regulations to promote sustainable food production industries are evolving (Christensen et al., 1996; Godfray et al., 2010; Reid et al., 2005). Therefore, finding more sustainable strategies to produce food is of critical importance.

Tightening nutrient cycles is prospectively a sustainable approach for food production that will minimize waste and damages to ecosystems (Delaide et al., 2017). Aquaponic food production is one potential solution to reduce adverse environmental impacts of food production such as eutrophication and water consumption (Cohen, Malone, Morris, Weissburg, & Bras, 2018; Xie & Rosentrater, 2015). In aquaponics, a seafood-producing environment (aquaculture) is integrated with a soilless plant-producing environment (hydroponics) with nitrifying and mineralizing bacteria serving as a filter in a symbiotic recirculating setup. Combining these systems is anticipated to be a more environmentally and economically sustainable food production process compared to separate aquaculture-agriculture processes and conventional agriculture and seafood harvesting (Adler, Harper, Wade, Takeda, & Summerfelt, 2000; Goddek et al., 2015; Xie & Rosentrater, 2015).

Aquaponic systems produce both seafood (typically fish) and vegetables. Currently, Nile tilapia (*Oreochromis niloticus*) is the most widely cultivated fish in aquaponic systems due to its resistance to temperature stress and poor water quality, fast growth rate, and tolerance to crowding (Nelson, 2017). However, other types of aquatic species such as ornamental fish, catfish (*Ictalurus punctatus*), yellow perch (*Perca flavescens*), rainbow trout (*Oncorhynchus mykiss*), and largemouth bass (*Micropterus salmoides*) have been grown in previous aquaponic studies (Love et al., 2015). This highlights the compatibility of aquaponics for the production of different seafood species, including walleye (*Sander vitreus*; the focus of this work), as their natural habitats are facing substantial management problems such as over-exploitation and species distribution change (Ormerod, 2003). With respect to the plant-producing part of aquaponics, leafy vegetables are the most commonly cultivated plants in aquaponic systems due to their short production period and high demand (Bailey & Ferrarezi, 2017; Love et al., 2014; Rakocy, 2012; Rakocy, Masser, & Losordo, 2006), although, herbs and tomatoes are also reported as economically viable plant types (Love et al., 2014).

Previous studies have used life cycle assessment (LCA) to quantitatively evaluate the environmental impacts of food production systems, including aquaponics (Aubin et al., 2006; Blidariu & Grozea, 2011; Cohen et al., 2018; Xie & Rosentrater, 2015). Cohen *et al.* (2018)

showed that aquaponics significantly reduced damages associated to human health, ecosystems, and resources by approximately 84%, 62%, and 48% respectively, compared to separate aquaculture and conventional agriculture systems. Aubin *et al.* (2006) found that using a recirculating system for fish growth instead of flow-through farming increases non-renewable energy use, acidification potential, and global warming potential by more than three times. Although they also found a decrease in water usage by 91%. In general, the current body of literature suggests that aquaponic food production is beneficial in decreasing some environmental impacts while increasing others compared to conventional food production systems. As suggested previously, further improvements to aquaponic systems to reduce associated environmental impacts seem possible with better management of nutrient emissions (Aubin et al., 2006).

Previously, energy consumption (largely for system heating/cooling) and feed have been reported as two hotspots of environmental impacts in aquaponic systems (Aubin et al., 2006; Boxman, Zhang, Bailey, & Trotz, 2017; AA Forchino, Lourguioui, Brigolin, & Pastres, 2017; Maucieri et al., 2018). Boxman *et al*. (2017) found a 20% decrease in aquaponic system energy and feed requirement can respectively contribute to a 14.8% and a 6.4% reduction in equivalent carbon dioxide (CO_2-e) produced during the aquaponic system operation. Delaide *et al*. (2017) concluded although aquaponics are very efficient alternatives in water use to produce fish and vegetables (278 liters (L) consumed per kilogram (kg) increase in tilapia), it is important to explore means to reduce energy consumption (96.2 kilowatt hour (kWh) utilized per kg increase in tilapia) to minimize total environmental impacts of aquaponics. In general, in warm weather regions, energy consumption is driven by heating/ cooling, pumping, and lighting, however, that may differ if the aquaponic system is utilized in weather cold weather regions.

In the current work, a holistic midpoint assessment, utilizing a comprehensive inventory and considering multiple impact categories, is performed on a research-scale aquaponic system, which cultivates multiple vegetable species as well as carnivorous hybrid walleye (*Sander vitreus x Sander canadensis,* aka saugeye) for the first time. Moreover, the main contributors of the system's environmental impacts will be addressed and real case scenarios using different practical alternatives will be evaluated to propose suggestions in order to further decrease potential aquaponic environmental impacts.

The paper is organized as follows: system description, methods utilized and modeling criteria is comprehensively described in section 2 (into three sub sections: system description, goal and scope definition, life cycle inventory). Afterwards, results and discussion for this analysis have been organized in section 3 (into seven sub-sections). Section 3.1 discusses the environmental impact assessment based on fish fillet production. Section 3.2 demonstrates the environmental impacts based on other functional units. Sensitivity analysis of the inventory inputs and outputs is performed in section 3.3. Finally, after identifying and evaluating the hotspots of the aquaponic system, the potential effects of using alternative scenarios for the major contributors of the aquaponic system is proposed and evaluated in sections 3.4 to 3.7 (fish food, equipment, electricity, and heating).

3.2. Methodology

LCA is a standardized tool conceived to assess the environmental impacts associated with a product or process. According to the International Standard Organization definition (ISO14040), LCA comprises four steps: goal and scope definition, inventory, impact analysis and interpretation (ISO-Norm, 2006). In the goal and scope definition, the explanation of evaluation methods, product system boundary, functional unit, and data parameters are made. In inventory stage, resources consumed and emissions to the environment at all stages of a process's lifespan are quantified (Guinée, 2002; ISO-Norm, 2006). In the third step, identification and evaluation of key issues are made. In the end, recommendations and conclusions are made in interpretation step (Lee & Inaba, 2004).

3.2.1. System Description

Six identical entry-level aquaponic systems, located at the University of Wisconsin-Stevens Point Aquaponics Innovation Center (AIC), were used; each consisting of two fish tanks, two clarifiers, two mineralization tanks, one communal bioreactor/degassing tank, four rafts, and a sump tank (Figure 5). Further details regarding the aquaponic system equipment (including lights, pumps, and polystyrene trays) and their lifespan, to quantify their amounts based on a one-year operational functional unit, can be found in Table A5 of the Appendix A.

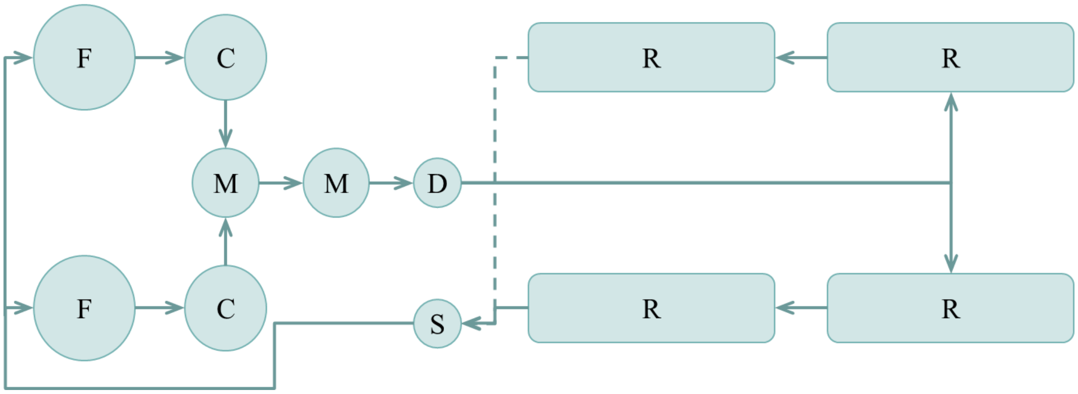

Figure 5. Overview of one of the six aquaponic labs at UW- Stevens Point Aquaponics Innovation Center (AIC); F: Fish Tank, C: Clarifier, M: Mineralization Tank, D: Degassing Tank/Communal bioreactor, R: Raft Tank, S: Sump Tank. Arrows show water flux direction.

In each aquaponic system, fish were fed protein and nutrient-containing commercial fish food. Consequently, the waste excreted contained dissolved nutrients, such as ammonia (NH_3), as a product of fish metabolism. The nutrient rich water was directed to the clarifiers to remove the majority of the solid waste. By means of mineralization and nitrifying bacteria, ammonia was oxidized into nitrite (NO_2^-) and then nitrate (NO_3^-), which was less harmful for aquatic species as well as a nutrient source for the plants. After degassing, the NO_3^- containing water was directed to the raft tanks, in which the plants consumed NO_3^- by absorbing water. In the end, water was directed to the sump tank, which acted as a controller for water level fluctuations in raft and fish tanks.

3.2.2. Goal and scope definition

3.2.2.1. Scope and system boundary

The main goal of this study is to determine the environmental impacts of an aquaponic food production system, located in a cold-weather region. The investigated system includes a comprehensive set of processes and factors that propose associated environmental impacts. The system boundaries include inputs (heat, equipment, electricity, fish food, water, seeds) and outputs in forms of product (fish fillet, vegetables) and waste (solids, non-fillet fish fraction, and non-edible vegetable fraction). As the final product of the system is unit mass of produced food (in the form of fish fillet, vegetables, or both) at the aquaponic gate, the current study is a cradle-to-gate assessment. Post-farm processes (e.g. packaging, transportation, distribution, use, end of use) were excluded from the scope of this assessment due to the lack of reliable data (no product commercialization for the investigated research-scale system) and potential variation in post-farm scenarios.

3.2.2.2. Evaluation criteria

3.2.2.2.1. Impact assessment method

SimaPro 8.2.0 was used for life cycle analysis as the modeling platform, using databases from Agri-footprint (Durlinger et al., 2014), Ecoinvent-3 (EcoInvent, 2014), European reference Life Cycle Database (ELCD) (Goedkoop, Oele, de Schryver, Vieira, & Hegger, 2008), and United States Life Cycle Inventory (USLCI) (Norris, 2004) databases.

The U.S.EPA’s Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) 2.1 was selected to assess environmental impacts as it considers the best applicable methodologies within each category in the United States, where the studied system is also located (Bare, Young, Qam, Hopton, & Chief, 2012). For each midpoint environmental impact category, the total quantity of chemical emission or resource utilized is multiplied by its estimated potency, which is based on the best available models and data (Aubin et al., 2006; Bare et al., 2012). The impact categories evaluated in this study (abbreviation, unit) are ozone depletion (OD, kg CFC-11 eq), global warming (GW, kg CO_2 eq), photochemical smog (PS, kg O_3 eq), acidification (AC, kg SO_2 eq), eutrophication (EU, kg N eq), human health carcinogenics

(HHC, CTUh), human health non carcinogenics (HHNC, CTUh), respiratory effects (RE, kg $PM_{2.5}$ eq), ecotoxicity (EC, CTUe), and fossil fuel depletion (FF, MJ surplus). Evaluating the system environmental impacts, using multiple impact categories provides the opportunity to have a holistic assessment and to analyze potential tradeoffs.

3.2.2.2.2. Sensitivity analysis

In order to quantitatively identify the input and output parameters to which the LCA results of the aquaponic system is sensitive (with corresponding changes in the impact results), a sensitivity analysis was performed (Boxman et al., 2017). For each parameter listed in the inventory, the value was modified by ± 20%. The updated impacts of the existing system were re-calculated to determine how the change in input affected the resulting environmental impacts for each impact category. The relative change of the output terms was compared with the relative change of the input terms to calculate the sensitivity factor (SF) (Cornejo, Zhang, & Mihelcic, 2013). Parameters with a sensitive factor of 2% or lower were considered negligible.

3.2.2.2.3. Functional unit

The functional unit is a quantified description of a studied system and it provides a reference to which the inputs and outputs can be related and compared (Rebitzer et al., 2004). Different mass-based functional units have been used previously for investigating aquaponic systems' environmental impacts, including the production of fish (Boxman et al., 2017), vegetables (AA Forchino et al., 2017), and combination of fish and vegetable (Hindelang, Gheewala, Mungkung, & Bonnet, 2014). In this study, as both fish and vegetable product are under consideration, three different functional units are defined and evaluated: one kilogram (kg) of hybrid walleye fish fillet produced, one kg of harvested vegetable (edible plant tops), and one kg of combined fish and vegetable produced based on mass ratio (9.82% fish fillet, 90.18% vegetable). The use of multiple functional units will also allow for a comparison across other current studies in the literature.

3.2.3. Life cycle inventory

In this cradle-to-gate analysis, production of fish (hybrid walleye) and vegetables (Butterhead lettuce (*Lactuca sativa*), Romaine lettuce (*L. sativa*), Kale (*Brassica oleracea, cv Starbor*), and Pak Choi (*Brassica rapa*)) are considered as the outputs of the system. Waste emissions in forms of biosolids and non-fillet fish segments are also considered. Fish food, water (initial filling volume and make up volume to compensate for evaporation, transpiration and leakages), electricity, heat (from natural gas), equipment, and plant seeds are considered as the inputs of the system. Further details and life cycle inventory (LCI) data can be found in Table A1 of the Appendix A. Figure 5 presents the scope and bounds of the assessment.

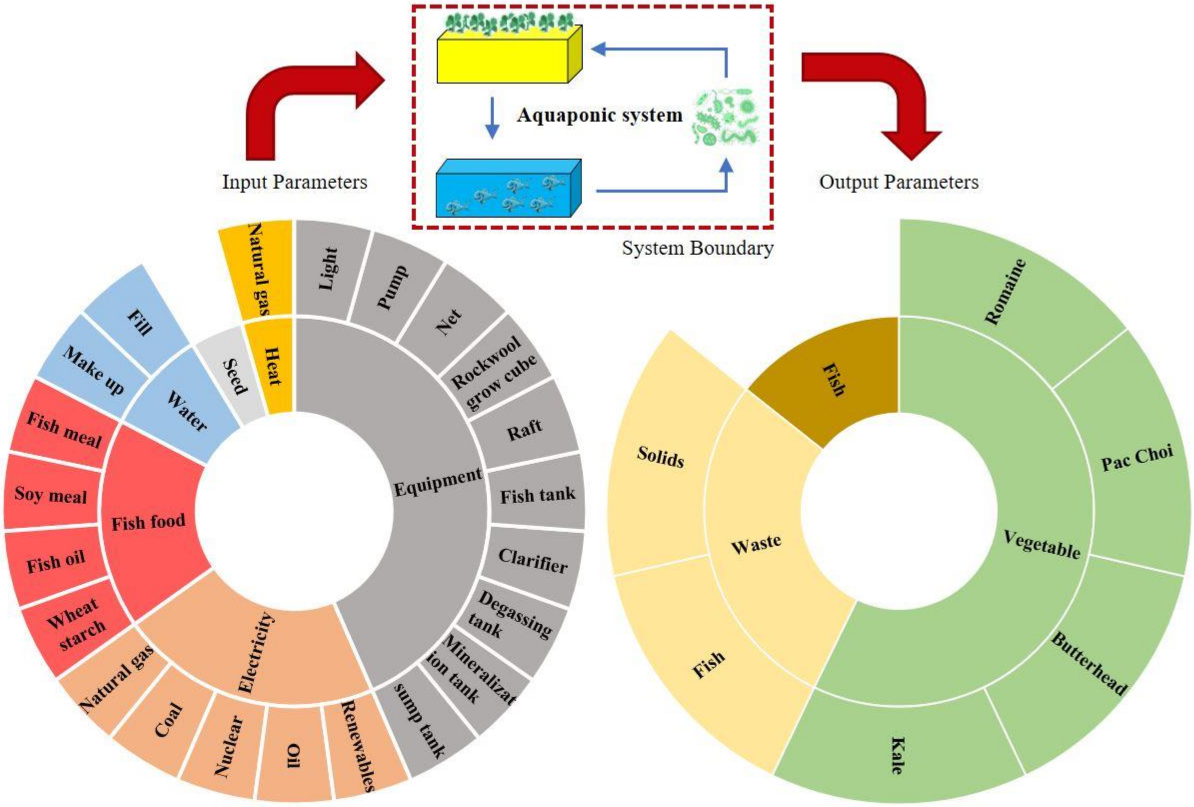

Figure 6. Life Cycle flow diagram of the aquaponic system.

3.2.3.1. Fish

Hybrid walleye (*Sander vitreus x Sander canadensis*, aka saugeye) were selected to be produced in the aquaponic system due to its local demand (as a native Wisconsin fish) and its resilience to low temperatures. Local demand in the state of Wisconsin (United States) is largely due to the cultural prevalence of the Friday night fish fry (WSJ, 2012). Thus, this is a more in-demand fish in Wisconsin than the commonly produced Nile tilapia (Revolinski, 2018).

Fish densities in aquaponic systems can vary (Boxman et al., 2017). Generally, increasing fish density results in a more nutrient-containing water, that consequently can increase plant growth yield. However, carnivorous fish, such as walleye, exhibit cannibalism at high densities, which can lower overall fish production. Additionally, extreme stocking densities promote outbreaks of pathogens and consequently decreases plant growth yields (Naylor et al., 2000). In order to achieve the optimal balance for plant and fish growth, three different fish densities were used in this project. Two systems were stocked with 66 fish/m^3 hybrid walleye fry; two with 132 fish/m^3 hybrid walleye fry; and two with 198 fish/m^3 hybrid walleye fry. Densities were determined using the aquaponics standard feed-rate ratio which is based on fish and plant nutrient needs and is currently the *de facto* method used in commercial aquaponics (Somerville, Cohen, Pantanella, Stankus, & Lovatelli, 2014). The non-edible parts of fish were composted after harvesting and obtaining the edible fish fillet.

3.2.3.2. Plants

Multiple vegetables including Butterhead lettuce (*Lactuca sativa*), Romaine lettuce (*L. sativa*), Kale (*Brassica oleracea, cv Starbor*), and Pak Choi (*Brassica rapa*) were grown at a density of 18 plants/m^2 for each variety in each aquaponic unit until harvested. The edible portions (top) and total harvested plant (including plant root) mass were measured to obtain total system plant production. The non-edible parts of plants were given away to pig and goat farmers to feed their livestock.

3.2.3.3. Fish food

Fish food has been previously found to be the largest material contributor to the environmental impacts of aquaponics in warm regions and in tilapia-based systems (Boxman et al., 2017; Cohen et al., 2018). There is a general motivation to move from fishmeal-containing ingredients toward plant-based protein sources due to the rising prices of fishmeal, and their relatively high environmental impacts (Hardy, 2010; Naylor et al., 2000; Rumsey, 1993). Moreover, resource limitations of forage fish (source of fish meal and oil in fish food) is a challenge for the future aquaculture sustainability, motivating aquatic-based industries to use alternative feed sources (Froehlich, Jacobsen, Essington, Clavelle, & Halpern, 2018).

The currently used fishmeal-containing diet (FMC#1; 55% protein, 15% fat, 1.5% fiber, 3% calcium, 2% phosphorus, 1% sodium), which contains fishmeal, soymeal, fish oil, and wheat starch were evaluated. Additionally, other fish food diets, including other fishmeal-containing (FMC#2, FMC#3) and fishmeal-free (FMF #1, FMF #2) diets, targeting 55% protein, were evaluated in order to investigate the effect of using different fish food ingredients on total environmental impacts (Bjerkeng et al., 1997; Soler-Vila, Coughlan, Guiry, & Kraan, 2009). Further details regarding different fish food formulas that are used in this study and their ingredients are presented in Table S2 of the SI.

3.2.3.4. Electricity

High use of energy in aquaponics is reported as a challenge in the literature (Delaide et al., 2017; Hollmann, 2017). In general, it is reported that using more renewable energy sources would decrease the environmental impacts associated with electricity consumption (AA Forchino et al., 2017). Current energy source allocations provided by the local electricity company (Alliant Energy), and their previous and prospective energy source allocations, were evaluated to recognize the relative environmental impacts of using different energy sources (*2017 Corporate Sustainability Report - Alliant Energy*, 2017). Further details regarding energy sources and other alternative ratios can be found in Table A3 of Appendix A.

3.3. Results

3.3.1. Environmental impacts

A quantitative assessment of the aquaponic food production process, attributed to the system inputs and outputs (Table A1 of Appendix A) based on one kg production of fish fillet over a one-year process is performed. Results are illustrated in Figure 7.

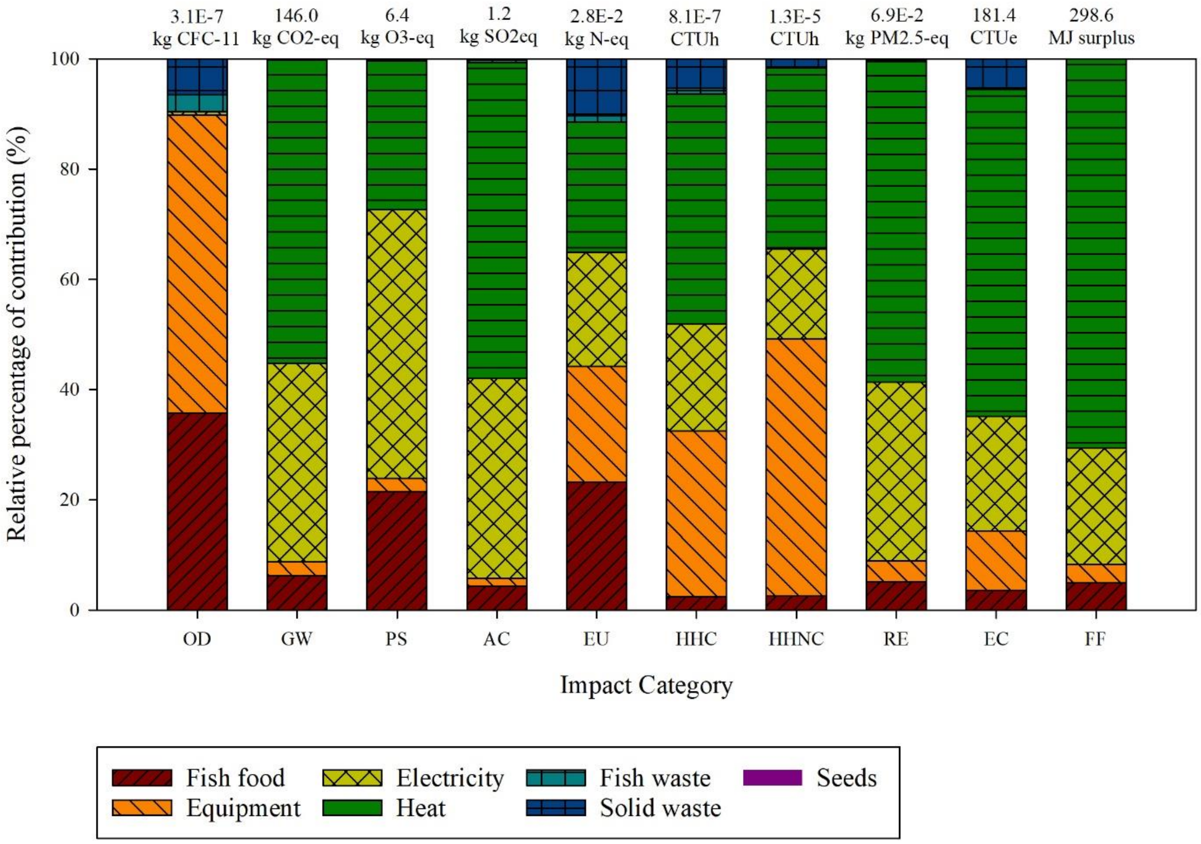

Figure 7. Total environmental impacts and parameters relative contribution for all investigated impact categories.

The analysis indicates that fish food, equipment, electricity, and heat are contributing more than 88% of environmental impacts in all categories. These parameters represent environmental hotspots in the aquaponic system analysis. In GW, AC, EU, HHC, RE, EC, and FF categories, heat is the most impactful contributor of the aquaponic system. In OD and HHNC, system's equipment is the most impactful contributor. Finally, in PS category, electricity is the most impactful contributor among all inventory inputs and outputs.

The integration of aquaculture and agriculture systems by aquaponics intensifies production in a small land area, conserves water, reduces waste discharged into the environment, and recovers nutrients from fish production into valuable vegetable crops (Bailey & Ferrarezi, 2017).

However, new added parameters to the combined system, such as the electricity required for water recirculation and lights, energy required for space heating, and additional equipment are subject to increased environmental impacts in different categories (e.g. AC and GW potential).

Production of one kg of carnivorous cold water fish fillet (considering a 55% on-skin fillet yield (JW Davidson et al., 2014; Einen, Waagan, & Thomassen, 1998)), in a conventional flow-through farm, contributes at least three times more environmental impacts compared to the aquaponic system in EU category, which is attributed to the higher emission of nutrient-rich waste in flow-through farming (Table 4). However, the aquaponic system has higher environmental impacts in GW and AC categories compared to conventional fish farming (at least 29 and 34 times higher, respectively).

Table 4. Comparison of relative environmental impacts for carnivorous cold-water fish production in aquaponic system and conventional farm.

Impact Category	Unit	Hybrid Walleye Aquaponic Fish farming [this study]	Hybrid Walleye Aquaponic Fish farming, heat & electricity excluded [this study]	Trout conventional fish farming (Aubin et al., 2006)	Trout conventional fish farming (Papatryphon et al., 2004)	Atlantic Salmon conventional fish farming (Nathan W Ayer & Tyedmers, 2009)
EU	kg N eq (Bare et al., 2012)	0.028	0.015	0.28	0.08	0.13
GW	kg CO2 eq	145.7	12.857	5.00	2.43	5.03
AC	kg SO2 eq	1.2	0.076	0.035	0.013	0.03

By excluding environmental impacts of heat and electricity from the aquaponic system, GW and AC impacts would be decreased by more than 91%. Therefore, significant impacts of the aquaponic system in GW and AC categories are mostly attributed to high system demand for heat and electricity. This suggests that for cold weather aquaponic operations, reducing heat and electricity usage could have a significant environmental benefit.

3.3.2. Harmonization of impacts using varying functional units

One of the main challenges in LCA of multi-functional systems (e.g. aquaponics) is selecting an appropriate allocation procedure (Cederberg & Stadig, 2003). Previous studies have selected different allocation approaches based on intended main product and co-product of their aquaponic system. Some of the studies have taken the aquaculture perspective, and demonstrated the results based on unit mass of produced fish (Boxman et al., 2017; Liu et al., 2016), while others demonstrated the results based on unit mass of produced vegetable (Andrea Forchino et al., 2018; Jaeger, Foucard, Tocqueville, Nahon, & Aubin, 2019). A few studies have applied a breakdown of co-product mass allocation of impacts to incorporate multi-functionality, and reported the results based on overall combined production of both fish and vegetables (Hindelang et al., 2014). In order to increase the transparency of the work, results are demonstrated based on the adoption of the allocation procedures from the aforementioned studies. As both fish and vegetable are the products of the aquaponic system, impacts based on one kg of vegetable (edible plant tops) and one kg product (9.82% fish fillet and 90.18% vegetable) are also calculated. Results for EU and GW categories are illustrated in Figure 8. Environmental impacts for all investigated categories are provided in Table A9 of Appendix A.

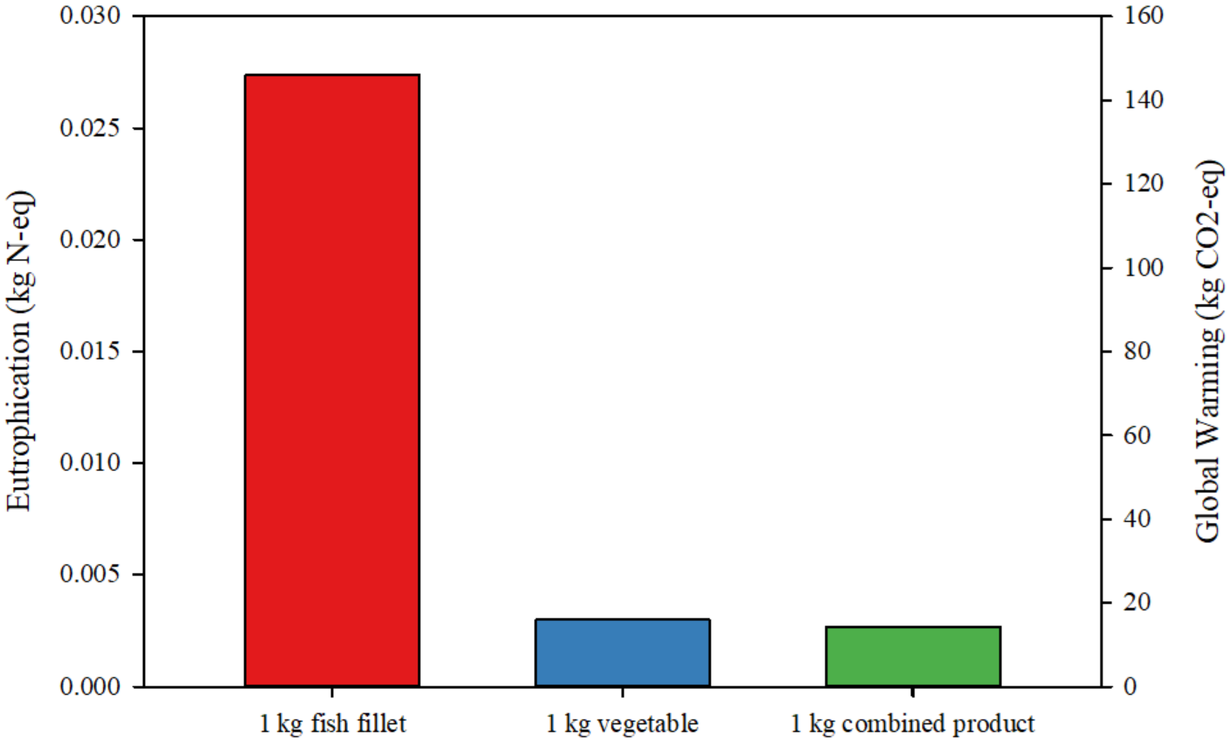

Figure 8. Impacts of system contributors in eutrophication (left vertical axis) and global warming (right vertical axis) according to different functional units.

As shown, demonstration of the results based on unit mass fish fillet functional unit will result in approximately 10 times higher impacts in all investigated categories compared to the demonstration of the results based on unit mass of vegetable or unit mass of total product functional units. This is due to the relatively large production of vegetables (838 kg) compared to fish fillet production (91 kg) over a 1-year period in the aquaponic system. Variation of the results based on different allocation procedures is highlighting the importance of results demonstration harmonized by diversified, commonly used functional units.

3.3.3. Sensitivity Analysis

For all of the 10 investigated environmental impact categories, a sensitivity analysis was performed, and Sensitivity Factors (SFs) were calculated. Results for major contributors are shown in Figure 9 and for all contributors are provided in Table A7 of Appendix A.

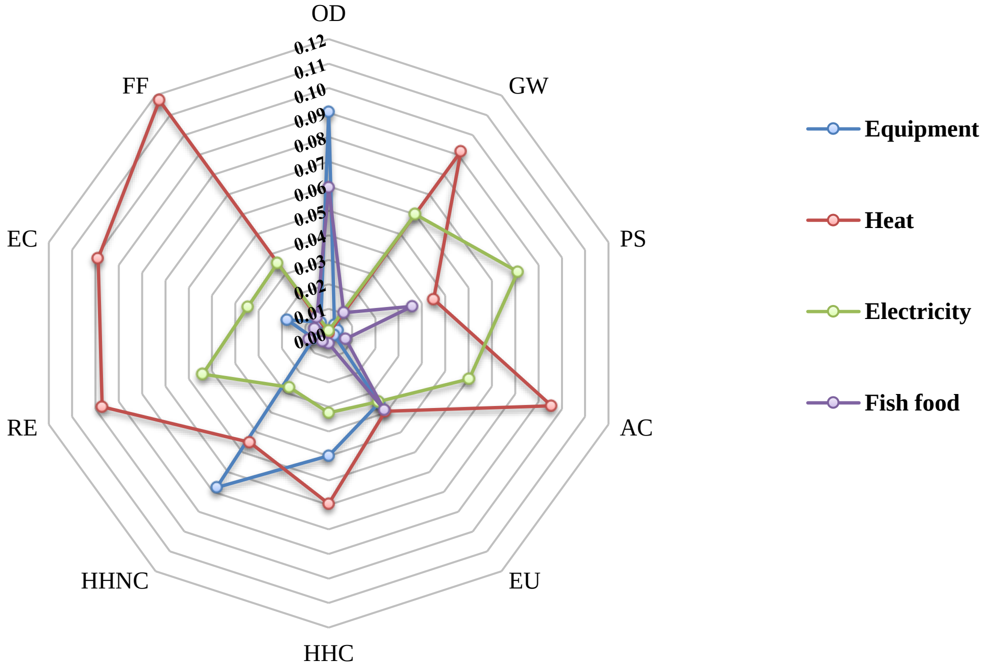

Figure 9. Sensitivity Factors for major contributors of system environmental impacts in different investigated categories.

With respect to OD, equipment (SF= 0.0901) and fish food (SF= 0.0594) is identified as two sensitive parameters. This indicates that the overall impact of the aquaponic system is not sensitive to the change in other investigated parameters but equipment and fish food, concerning ozone depletion potential. In GW, AC, RE, EC, and FF categories (5 out of 10 investigated impacts), electricity and heat is identified as the only two sensitive parameters (SFs = 0.0918, 0.0957, 0.0971, 0.0988, 0.1178 for heat and 0.0601, 0.0604, 0.0540, 0.0347, 0.0355 for electricity regarding GW, AC, RE, EC, and FF respectively). This highlights the importance of energy parameters (heat and electricity) in overall environmental impacts of the investigated aquaponic system. With respect to human health impact categories (HHC and HHNC), equipment (SF= 0.0499 for HHC and SF= 0.0777 for HHNC) is identified as an additional sensitive parameter, besides heat (SF= 0.0695 for HHC and SF= 0.0549 for HHNC) and electricity (SF= 0.0324 for HHC and SF= 0.0271 for HHNC). Therefore, for the investigated aquaponic system and human health related impact indicators, neglecting the overall impact of system equipment is shown to be not valid. In PS, fish food were recognized as another sensitive parameter (SF= 0.0359), in addition to heat (SF= 0.0918) and electricity (SF= 0.0601). Therefore, the impacts associated with fish food production may not be neglected, especially in areas that photochemical smog is an issue (e.g. urban regions). EU is the only impact category, in which all the sensitive parameters have shown sensitivity (SFs are 0.0395, 0.0345, 0.0346, 0.0388, for heat, electricity, equipment, and fish food, respectively). Therefore, in order to address the environmental impacts of eutrophication associated with the cold-weather located aquaponic system, there is a need to incorporate all the aforementioned parameters.

The SFs for seed production, fish waste and solid waste are negligible (<2%) for all impact categories. Contrarily, in nine impact categories, heat has SF of >0.02; and in seven impact categories, heat has the highest SF among all other parameters (GW, AC, EU, HHC, RE, EC, FF). Therefore, a small change in space heating in the aquaponic system could significantly change the total environmental impacts of the system. This emphasizes the importance of optimizing heating techniques in cold weather locations, where there is a high difference between the greenhouse inside and outside average temperature over a 1-year period. Additionally, electricity has SF of >0.02 in nine impact categories (all except OD). Fish food and equipment also impose non-negligible SFs in three (OD, PS, EU) and four (OD, EU, HHC, HHNC) impact categories, respectively. Therefore, the environmental impact sensitive parameters of the aquaponic system are respectively identified as heat, electricity, equipment, and fish food. As shown previously, heating contributes significantly to the overall environmental impact of the production system in a cold weather environment, and thus it is critical to reduce heating needs.

3.3.4. Fish food scenarios

Comparative potential environmental impacts for using multiple commercial fish foods (the one utilized in this system plus four others) were evaluated and illustrated in Figure 10. Fishmeal is one of the main contributors of environmental impacts in fish food ingredients (utilized ingredients for alternative diets are quantified in table A2 of Appendix A). It is suggested that eliminating the use of fishmeal as an ingredient for fish food production and substituting it with other fishmeal-free ingredients could lead towards a more sustainable fish food. Additionally, there is a growing concern that the use of fishmeal as a fish feed source is contributing to the prevalence of antibiotic resistance in bacterial communities (Han et al., 2017). However, it is critical to be aware of unintended consequences when deciding to select the fish diet.

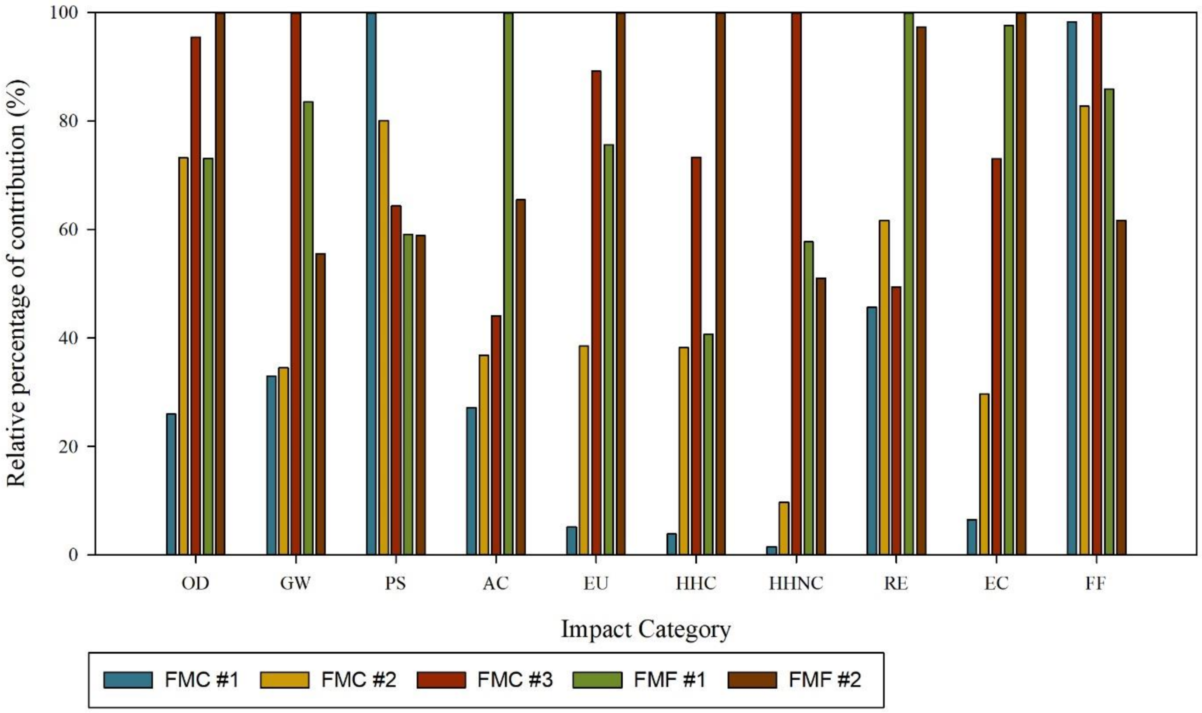

Figure 10. Relative Fish food production environmental impacts using different fish food ingredients (based on produced unit mass of fish food with equivalent protein content). Different fish foods are the currently used fishmeal-containing feed (FMC #1), two other fishmeal-containing feeds (FMC #2, FMC #3), and two fishmeal-free feeds (FMF #1, FMF #2).

Results show that the substituted materials in fishmeal-free diets, especially poultry meal and soybean, may be even more environmentally impactful than using fishmeal. The currently used fishmeal-containing fish diet (FMC #1) has the lowest environmental impacts in 8 out of 10 investigated impact categories, compared to the potential impacts of four other fish diets, including two fishmeal-free diets (Figure 10). Additionally, fishmeal-free diets contain fish oil, preventing them from being fully independent on rendered forage fish (Froehlich et al., 2018). However, it is necessary to mention that the investigated impact categories do not capture issues like resource depletion in the aquatic food web, which is a critical area of future research. Sensitivity factors of different fish food ingredients are quantified in Table A8 in Appendix A.

3.3.5. System equipment scenarios

Love *et al.* (2014) conducted a survey among 809 aquaponic holders, mostly in the US (80%), which showed that nearly nine in ten respondents (89%) had <5 years of experience with aquaponics, and over half of respondents (52%) had <3 years of experience with aquaponics. Comparative impact assessment of equipment, considering a 3-year and 5-year operation is also performed in order to have the most precise impact assessment for short-term aquaponic operation. Results are illustrated in Figure 11.

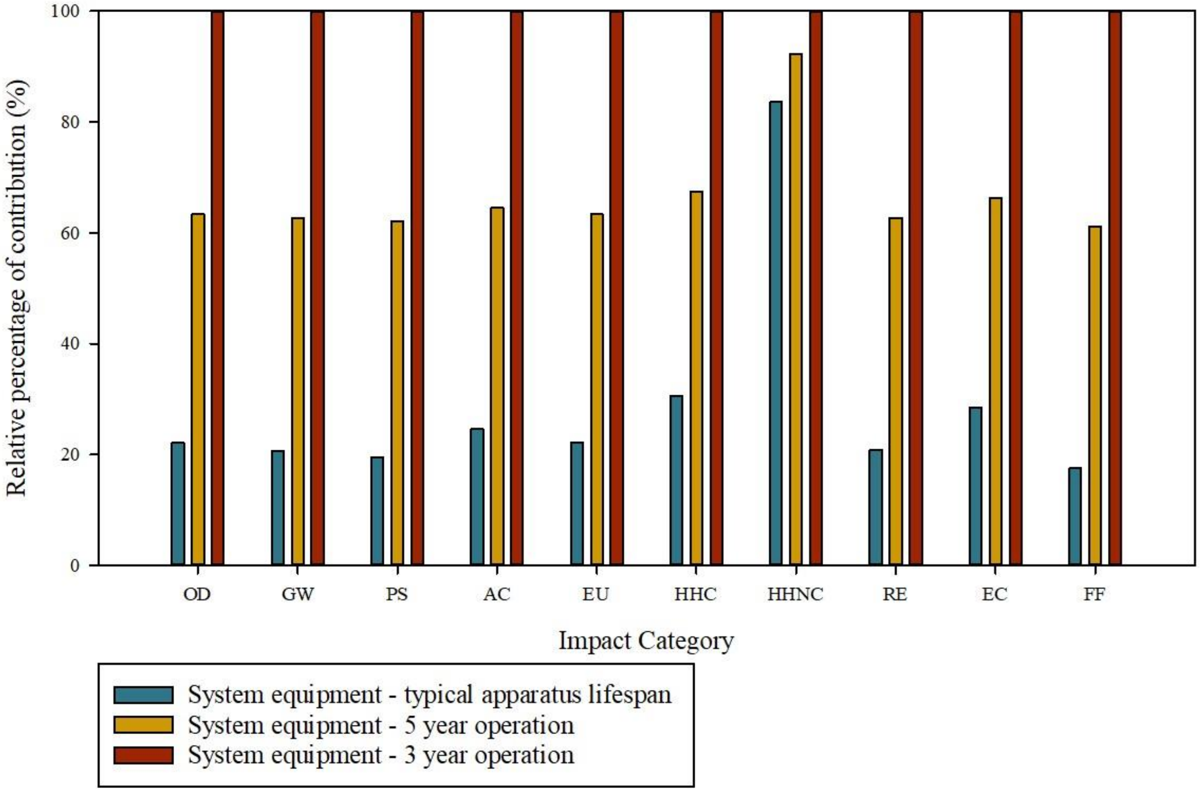

Figure 11. Relative system equipment environmental impacts based on different lifespan scenarios (typical apparatus lifespan, 5-year operation, and 3-year operation, impacts are quantified based on required equipment for one lab)

equipment has a variable lifespan, ranging from a fraction of a year (such as the rock wool growing media) to more than 20 years (such as high-density polyethylene tanks). Using the equipment for the maximum lifespan, contributes to a significant decrease in equipment potential environmental impacts. For example, when there is a 3-year operation for the aquaponic system, potential GW caused by system equipment is 263 kg CO_2-eq, which is 4.9 times higher compared to a long run (20 year) operation (54 kg CO_2-eq).

3.3.6. Electricity scenarios

The energy provider for the studied aquaponic system (Alliant Energy) is transitioning its energy sources to higher portions of natural gas, renewables, and less portions of coal, nuclear and oil (Figure 12, quantified resource portions are provided in Table A3 of Appendix A).

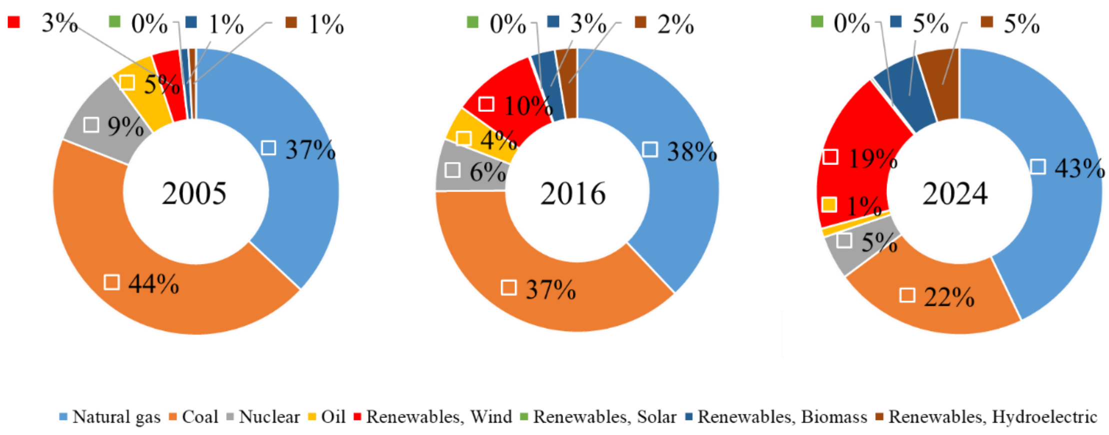

Figure 12. Electricity generation resource fractions (used by the studied aquaponic system) for 2004, 2016, and 2024 (reported by Alliant Energy (2017 Corporate Sustainability Report - Alliant Energy, 2017)).

This transition is influencing the potential environmental impacts resulting from electricity used in the aquaponic system. Comparative potential environmental impacts for electricity using different resource scenarios based on energy provider's resource ratio on 2005, 2016, and 2024 are shown in Figure 13.

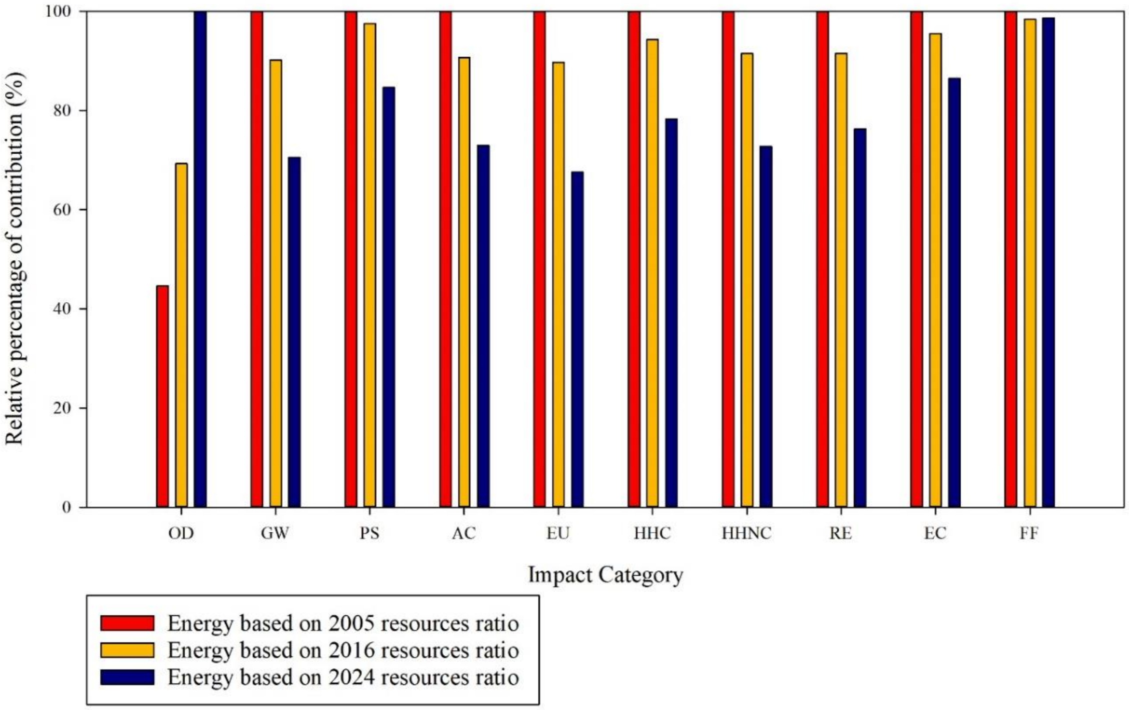

Figure 13. Relative electricity environmental impacts using different resource scenarios for generation of 1 kWh electricity.

For nine investigated impact categories (all except OD), potential impacts based on 2024 resource ratio are less than potential impacts based on 2005 resource ratio. This decrease is mostly attributed to the decrease in resource portion from coal (by two times) and increase in resource portion from renewables (by six times) (Akella, Saini, & Sharma, 2009; IEA, 1998; Quaschning, 2019; Sousa, Lagarto, Camus, Chaves, & Piedade, 2016). For OD, potential impacts based on 2024 resource ratio are higher than potential impacts based on 2005 resource ratio. This increase is mostly attributed to the increase in resource portion from hydroelectric power (by six times), which has a high contribution in ozone depletion potential. Moreover, electricity usage in the aquaponic system can be decreased by optimizing effective lighting, pumping, and inline heating/chilling (Bukhari & Ahmed, 2017; J. A. Nelson & Bugbee, 2014).

3.3.7. Heating alternatives

As determined in section 3.3, heat is the most sensitive parameter in the aquaponic system (Sf > 0.02 in 9 impact categories, highest SF in 7 impact categories among all investigated parameters). Therefore, it is important to optimize the volume of space in which the system is implemented to reduce the required heat. In the current system, 14% of the greenhouse volume is occupied by the aquaponic system. However, when considering total space volume and the heat needed for the total greenhouse volume, a significant potential impact increase in all impact categories will be observed. Comparative environmental impacts of the total aquaponic system using effective space heating and total space heating is demonstrated in Figure 14.

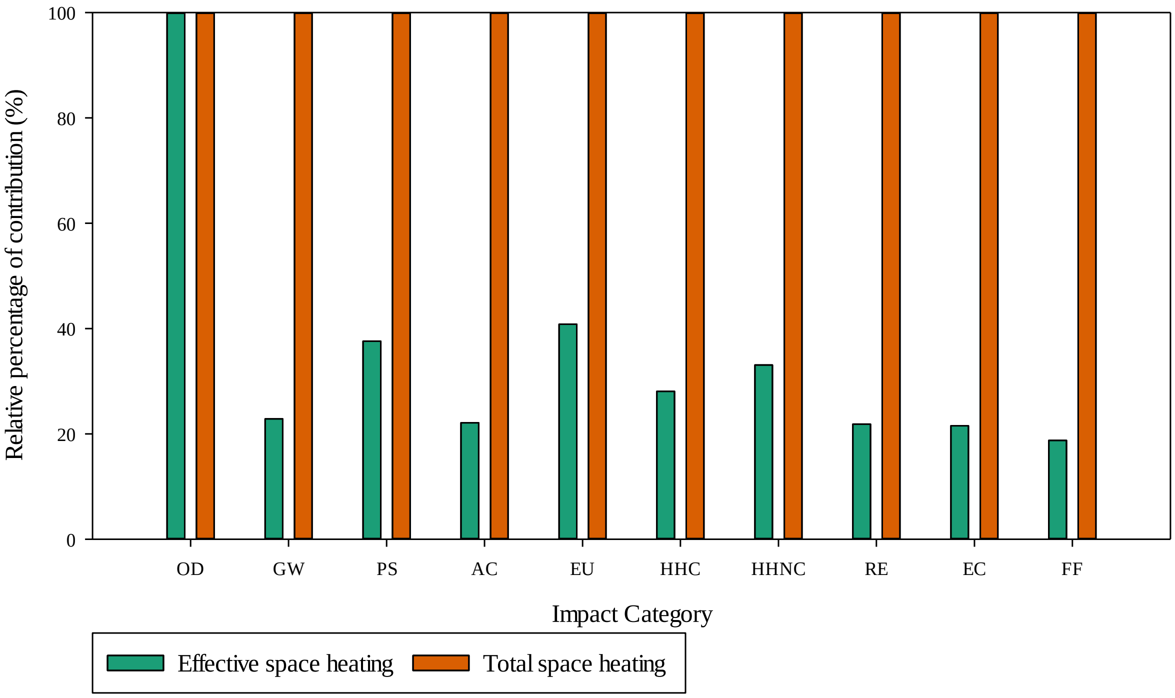

Figure 14. Relative total system environmental Impacts for using different heating scenarios based on total system heating requirement over one-year operation.

In nine impact categories, in which heat is a sensitive parameter (all except OD), effective space heating results in at least 2.4 times less impacts compared to total space heating.

As there is a high difference between greenhouse indoor and outdoor average temperature in cold weather regions, effective space heating can decrease waste of heating energy and its consequent environmental impacts (Antipova, Boer, Guillén-Gosálbez, Cabeza, & Jiménez, 2014; J. Wang, Zhai, Jing, & Zhang, 2010). Improvements in space heating can be accomplished by better insulation practices (bubble wrap or solid partitions within the greenhouse), better heater position (open central spots and away from water pipes) and use of heated propagators. This also suggests that for future aquaponic installations in cold weather areas, the quantity of space that must be heated is a critical consideration.

In summary, tightening food production cycles is a promising strategy to meet the world's growing food demand. Aquaponic food production is a leading method that implements this strategy for symbiotic aquatic species-plant production, while mitigating waste emission damages to the ecosystem (e.g. nutrients resulting in EU potential). However, means to reduce the potential environmental impacts associated with the required materials (e.g. food, equipment) and energy (e.g. electricity, heat) inputs need to be assessed in order to advance the environmental sustainability of aquaponic systems.

3.4. Discussion

Neglecting impact contributors, prior to performing life cycle assessment, is reported as one of the controversial issues in LCA of different processes and systems, including aquaponics (Finkbeiner et al., 2014). This work aimed to perform an LCA of a cold-weather located aquaponic system, using a comprehensive set of system inputs and outputs that may or may not have significant relative environmental impacts. This provides the opportunity to quantitatively identify the parameters that could be neglected, as well as the parameters that have the biggest contribution to the overall environmental impacts (impact hotspots).

After collecting the necessary information (material inputs and outputs of the system, energy requirements different forms, etc.), quantifying the environmental impacts, and performing sensitivity analysis, four parameters were identified as the environmental impact hotspots of the investigated aquaponic system: heat, electricity, equipment, and fish food.

The higher energy use in recirculating systems such as aquaponics compared to non-recirculating conventional systems is highlighted in previous studies (Aubin et al., 2009; Boxman et al., 2017). This increase in energy use results in potentially higher environmental impacts, in which energy-related parameters are sensitive (e.g. global warming potential). Moreover, the investigated aquaponic system is located in a cold-weather region, in which the extra heating demand is expected to increase the consecutive environmental impacts. Table 5 illustrates the difference among the current system energy use and global warming potential with two other warm-weather located systems.

Table 5. Energy requirement and global warming potential differences among the current cold-weather located recirculating system and two other warm-wear-located recirculating systems.

Study	Location	Average annual temperature (during study year, °C)	Energy Use (in MJ / kg fish produced)	GW (kg CO_2-eq / kg fish produced)
Boxman et al. (2017)	Florida, US	19.8	112.0	8.64
Aubin et al. (2009)	Brittany, France	11.1	290.9	6.02
This work	Wisconsin, US	8.7	1,524.8*	145.7

* Energy use is quantified as the summation of heat and electricity requirements (in MJ) for the investigated system

Energy use (integration of heat and electricity) in the cold-weather located system investigated in this study is significantly higher than the two aquaponic systems, located in warmer areas. As a result, due to the fact that heat and electricity were identified as the only sensitive parameters in GW, the consecutive GW impacts of the cold-weather located system is significantly higher than the warm-weather located ones.

In support of what (Boxman et al., 2017) declared, despite the relatively high energy requirement of the aquaponic system, practical approaches to optimize energy use (e.g. effective space heating) and the use of more renewables in electricity is shown to be highly feasible in reducing the overall potential environmental impacts of the aquaponic system.

Equipment is another identified environmental impact hotspot in this study. Equipment is often excluded from the studies due to the assumption of comparatively minor environmental impacts (Henriksson et al., 2012). However, quantification of environmental impacts associated with system equipment (based on effective lifespan operation) have shown that this assumption is not necessarily valid. More specifically, equipment is the most sensitive parameter in OD, and a sensitive parameter in EU, HHC, and HHNC impact categories. The relative contribution of equipment in overall environmental impacts also increases by short-term operation of aquaponic system (lower lifespans).

Another identified environmental impact hotspot of the aquaponic food production system is fish food. Moreover, the use of finite resources to provide fishmeal is an environmental restriction in fish food production (Tacon & Metian, 2008). Result of this work indicate that the fishmeal free diets does not contribute to lower potential environmental impacts compared to the fishmeal containing diets in investigated impact categories. As Papatryphon et al. (2004) also concluded, alternatives to replace fishmeal are usually energy-intensive (e.g. plant based proteins) and may require more material inputs and emission to provide equivalent amounts of nutrients. Therefore, a more precise investigation is required to identify alternatives and develop fish foods with comparable efficiency and lower overall potential environmental impacts.

3.5. Conclusions

This study presents a midpoint life cycle assessment for a carnivorous fish producing aquaponic system, located in a cold weather region, in ten impact categories. Heat, electricity, equipment, and fish food are the four environmental impact hotspots of the aquaponic system. The analysis performed in this study emphasizes the importance of applying optimization techniques in order to reduce the environmental impacts associated with the aforementioned impact hotspots.

Considering significant contribution of impacts from heat in nine impact categories, a minor reduction in heat consumption for the aquaponic system can result in a major reduction in overall environmental impacts. Effective heating practices should be regarded as a prime concern to mitigate adverse environmental impacts associated with space heating, along with consideration of heat sources (i.e. fossil fuels vs renewable fuels). Potentially co-locating these facilities with industrial practices that produce waste heat may be a viable option.

Electricity is found to be the second sensitive parameter in the aquaponic system. The current resource transition of the electricity sector towards using more renewables and less coal, as well as utilizing more efficient lighting and pumping practices in the aquaponic system is found to reduce environmental impacts associated with electricity.

System equipment and fish food is found to be the third and fourth sensitive parameters in the aquaponic system, respectively. Long-term operation of the aquaponic system based on equipment’s lifetime and the use of fish food ingredients with less associated impacts is found to contribute to relatively significant impact reduction in four and three impact categories, respectively. The push to move away from fishmeal-based protein sources may actually increase the environmental impact of the fish food production and thus the aquaponic fish production. More research is needed to fully investigate the environmental impacts associated with fish foods, and the potential for overfishing due to the need for forage fish.

Ultimately, as aquaculture is the fastest growing major food sector in the world, integration of aquaculture and agriculture systems using aquaponics will gain more attention due to their multi-functionality, production intensification in small land area, and reducing overall water consumption and waste emissions to the environment. However, techniques to reduce heat and energy consumption are necessary to be executed in future studies.

3.6. Acknowledgement

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Oceanic and Atmospheric Administration (NOAA). The views presented by the authors have not been formally evaluated by Sea Grant and therefore are reflective for the authors' views only. Any brand name products mentioned are for informational purposes only, and are not an endorsement. The authors gratefully acknowledge University of Wisconsin-Stevens Point Aquaponics Innovation Center (AIC) for providing data regarding the operation of the aquaponic system and Nelson & Pade, Inc. for assisting with data collection and operational advice. We would also like to thank Olivia Ernst at University of Wisconsin-Madison Writing Center and Sarah Jacobsen at University of Wisconsin-Madison College of Engineering for their contribution in this study.

4. Chapter 4: Comparative environmental impact assessment of aquafeed production: Sustainability implications of forage fish meal and oil free diets.

This chapter was adapted from: Ghamkhar, R., & Hicks, A. (2020). Comparative environmental impact assessment of aquafeed production: Sustainability implications of forage fish meal and oil free diets. Resources, Conservation and Recycling, 161, 104849.

The article appears as published, although style and formatting modifications have been made. After identification of Aquafeed as one of the impact hotspots in aquaculture and aquaponic food production systems (chapters 1 and 2), a comparative holistic analysis of varying aquafeeds with different ingredients inclusion is performed.

Authorship contribution statement

Ramin Ghamkhar: Designed Research, Performed Research, Analyzed Data, Wrote the Paper.

Andrea L. Hicks: Designed Research, Provided Feedback, Wrote the Paper.

4.1. Introduction

Due to the increasing global population (UNDESA, 2017) and concurrent rise in of consumption marine-based proteins per capita (FAO, 2009), aquaculture is the fastest growing major food production sector in the world. According to the Food and Agriculture Organization of the United Nations (FAO), the average annual growth in aquaculture production between 2000-2016 was 5.8%. This growth is expected to continue, and it is predicted that 60% of the fish available for human consumption will be provided by aquaculture in 2030 (FAO, 2018). In order to support sustainable aquaculture development and support the current growth of aquaculture, there is a critical need to mitigate the environmental impacts of aquaculture food production systems (FAO, 2018; Papatryphon et al., 2004).

Aquafeed has been previously identified as one of the most environmentally impactful parameters of aquaculture systems in conventional impact categories (e.g. global warming) (Bosma, Anh, & Potting, 2011; Ghamkhar, Hartleb, et al., 2020; Samuel-Fitwi et al., 2013; Wu et al., 2019). In addition, it is estimated that the aquaculture sector consumes 68.2% of total global fish meal production and 88.5% of total global fish oil production, making it highly dependent on marine capture fisheries (e.g. forage fish) for sourcing key dietary nutrient inputs (e.g. amino acids) (Tacon & Metian, 2008). The high dependency of ever-growing aquaculture food production on fish meal and fish oil, as well as the upward trends in fish meal and fish oil prices (Msangi et al., 2013; Tacon & Metian, 2008) have challenged the long-term ecological and economical sustainability of aquaculture food production systems. The international export fish meal and fish oil prices based on US Dollar / ton over time are illustrated in Figure 15 (Nations, 2019).

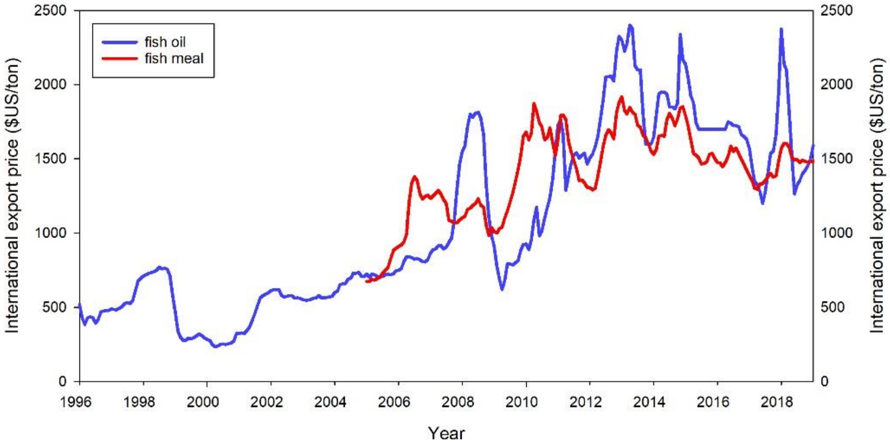


Figure 15. International export price trends for fish meal (from January 2005 to June 2019) and fish oil (from January 1996 to June 2019) in US$ per metric ton.

Aquaculture demand of finite marine resources is predicted to outstrip global supplies within the next decade (N Pelletier & Tyedmers, 2007). Therefore, to achieve sustainable aquaculture production, producers are seeking alternative feed ingredients to substitute marine-based fish meal and fish oil in the feeding formulations (Bendiksen, Johnsen, Olsen, & Jobling, 2011).

Various alternative ingredients, derived from plants and animals, have been formulated and used in an effort to fully or partially substitute fish meal and fish oil in aquafeeds (John Davidson et al., 2016; IP Forster, Dominy, Obaldo, & Tacon, 2003; Lazzarotto, Médale, Larroquet, & Corraze, 2018; Oliva-Teles, Enes, & Peres, 2015; Stone, Hardy, Barrows, & Cheng, 2005). As a result, trends indicate reduced inclusion rates of fish meal and fish oil in industrial aquafeeds (Naylor et al., 2009). However, total fish meal and fish oil use have continued their upward consumption trends due to the overall increase in global aquaculture production (Naylor et al., 2009; Tacon & Metian, 2008). It is anticipated that fisheries and aquaculture industries will expand their efforts to substitute marine-based ingredients with practical alternative nutrients in future years.

Despite the vital need to move towards aquafeeds with less dependency on biotic resources to provide essential nutrients, it is necessary to quantitatively evaluate the environmental impacts of aquafeeds containing different ingredients. Previous evaluations have typically used a limited set of impact categories (global warming, eutrophication, acidification, and energy demand (Bohnes & Laurent, 2019)), and neglected some crucial indicators of aquafeeds and aquacultures environmental sustainability, such as biotic resource depletion (Bohnes & Laurent, 2019; Henriksson et al., 2012). To prevent unintended consequences through burden shifting, an evaluation should be performed utilizing a comprehensive set of relevant impact categories, both in terms of resource depletion (e.g. water intake, biotic resource use) (Calone et al., 2019; Damerau, Waha, & Herrero, 2019; Goddard & Al-Abri, 2019) and pollutant emissions (e.g. eutrophication, photochemical smog) (Ghafari, Ghamkhar, & Atkinson, 2019; Ghamkhar, 2018; Silvenius et al., 2017; Zheng, Jin, Zhang, Wang, & Wu, 2019). Moreover, it is also critical to consider the efficacy of these aquafeeds with respect to the quantity and quality of the produced fish.

Life cycle assessment (LCA) has been applied previously to aquafeeds (Aubin et al., 2009; Ghamkhar, Hartleb, et al., 2020; Hognes, Nilsson, Sund, & Ziegler, 2014; Papatryphon et al., 2004; Nathan Pelletier et al., 2009; Silvenius et al., 2017). Quantification of the environmental impacts of different aquafeeds provides the opportunity to perform a comprehensive impact analysis and comparison among alternative aquafeed production scenarios. Previous studies have performed LCA on hypothetical aquafeeds, revealing that feed ingredient composition improvement of aquafeeds is necessary to mitigate the use of fishery resources (e.g fish meal) and nutrient emissions at the farm (Papatryphon et al., 2004; N Pelletier & Tyedmers, 2007). However, they have neglected to analyze the impact of the different theoretical aquafeeds on the quality of the seafood produced.

In this work, LCA is performed on twelve successfully formulated and tested (actually fed to aquaculture species) aquafeeds, containing various ingredients (e.g. fish meal free and fish oil free diets). Environmental impacts with respect to biotic resource use, water intake, and conventional Tool for the Reduction and Assessment of Chemicals and other environmental Impacts (TRACI) impact categories (Bare et al., 2012) are quantified and evaluated to provide a holistic analysis on the environmental impacts of traditional aquafeeds as well as alternatives that are utilizing different strategies for fish meal and fish oil replacement. In the end, suggestions to shift toward less environmentally impactful aquafeeds, considering the protein inclusion of investigated diets and fish production (feed efficiency), are made.

4.2. Methodology and Evaluation Criteria

Life cycle assessment (LCA) is a standardized method conceived to assess the environmental impacts associated with a product or process. According to the International Standards Organization definition (ISO14040), LCA is comprised of four steps: goal and scope definition, inventory, impact analysis and results interpretation (ISO, 1997). In the goal and scope definition step, the motivation to perform LCA, product system boundary, functional unit, and data parameters are defined. In the inventory stage, resources consumed and emissions to the environment at all stages of process lifespan, from the raw material extraction to the disposal of waste, are quantified (Guinée, 2002; ISO, 1997). In the third step, identification and evaluation of key issues are made. In the end, recommendations and conclusions are made in interpretation step (Lee & Inaba, 2004). In this study, the SimaPro 8.2.0 modeling platform was used for LCA, using databases from Agri-footprint (Durlinger et al., 2014), Ecoinvent-3 (EcoInvent, 2014), and United States Life Cycle Inventory (USLCI) (Norris, 2004) databases. For processes with multiple products (e.g. for fish meal from trimmings), mass allocations have been selected to handle multi-functionality.

4.2.1. Statistical Analysis

For all investigated impact categories except BRU, the uncertainties associated with the unit processes in the life cycle database were analyzed using Monte-Carlo simulations in SimaPro 8.2.0, for 1000 runs to the 95th confidence interval. Uncertainty analysis for the BRU impact category is not conducted due to the lack of data on the unit processes distribution.

To determine if there is a statistically significant difference between the mean impacts for two selected independent datasets from Monte-Carlo simulation, t-test analysis (two-sample mean-comparison test) with a confidence level of 95 is performed using Stata/SE 16.0. For any performed t-test, t-value (t) and p-value (p) were calculated. If $p < 0.05$, it is considered as a statistically significant.

4.2.2. Goal and Scope: System's Boundary

The main goal of this study is to determine the comparative environmental impacts of aquafeed production, based on varied practiced ingredients. In order to investigate the varying environmental impacts among aquafeeds with different ingredients, a cradle to gate (ingredients material acquisition and manufacturing) LCA approach is selected to be executed on successfully formulated, tested and used aquafeeds. The included/excluded parameters in the assessment criteria is illustrated in Figure 16.

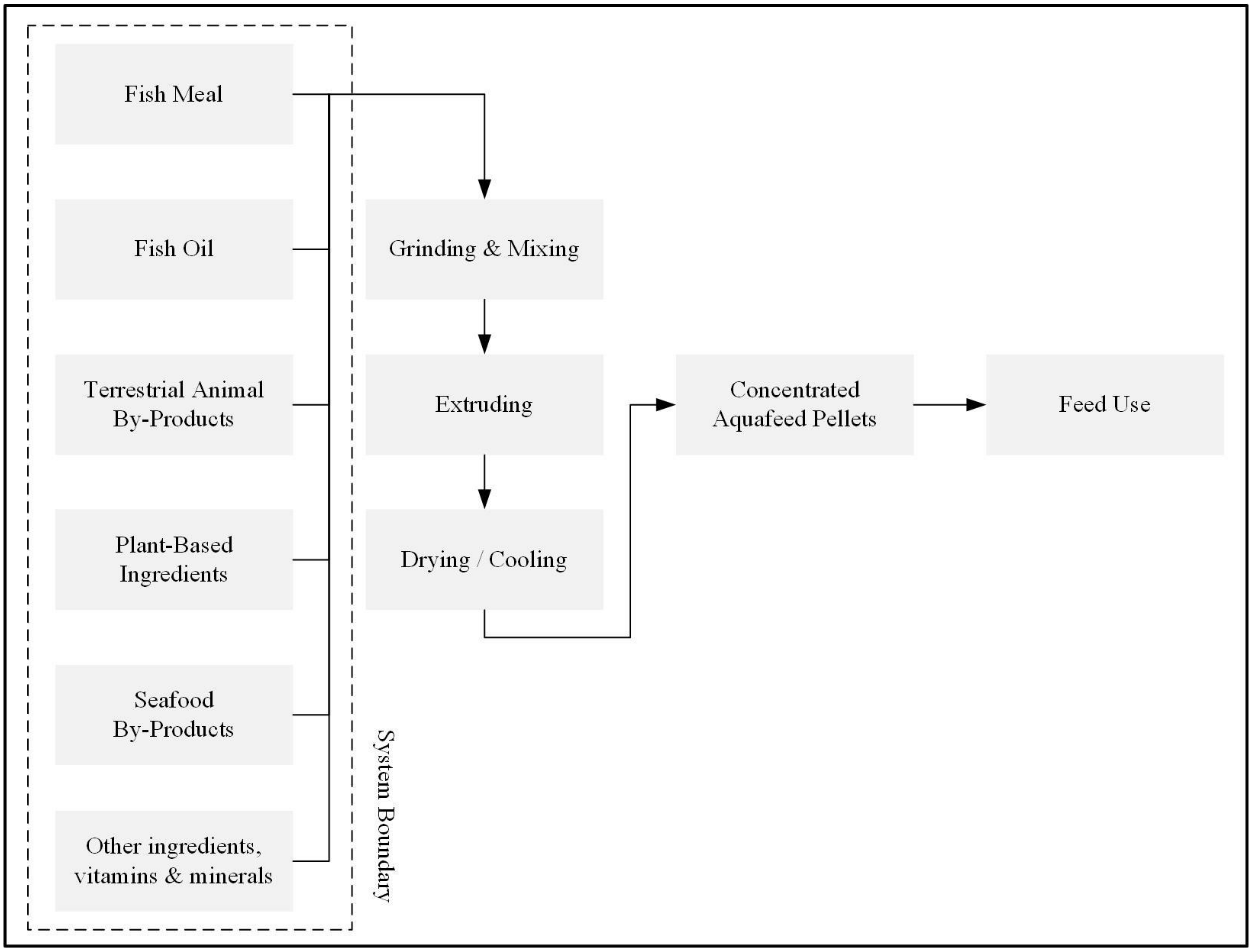


Figure 16. Life Cycle Inventory framework for aquafeeds production.

The environmental impacts of aquafeed production, using different ingredients will be evaluated and assessed based on associated ingredients and impact characterization factors. The impacts associated with the proceeding processes (i.e. grinding, extruding, drying, etc.) are excluded from the assessments due to similar requirements and processes among different diets.

4.2.3. Functional Unit

The functional unit (FU) is a quantified description of a studied system and it provides a reference by which inputs and outputs can be related and compared (Rebitzer et al., 2004). In many comparative analytical techniques, including LCA, functional unit is a central consideration (Pourzahedi & Eckelman, 2015). Mass-based functional units have been used previously for investigating the impacts of varying aquafeeds (Iribarren, Moreira, & Feijoo, 2012; N Pelletier & Tyedmers, 2007; Yacout et al., 2016). However, the comparative evaluation of aquafeeds' impact based on unit mass of produced aquafeed as the only FU ignores the variation in aquafeeds' nutritional characteristics, properties, and ultimate efficiency. To account for properties and characteristics of aquafeeds, two alternate functional units are utilized in this study: (a) aquafeeds unit protein provision (De Silva & Anderson, 1994), and (b) seafood unit live weight production (Abdou, Lasram, Romdhane, Le Loc'h, & Aubin, 2018; Aubin et al., 2009; Papatryphon et al., 2004). Consideration of varying FUs has also provided the opportunity to increase transparency of the results across studies with different perspectives regarding aquafeeds production with respect to the system's final product (Ghamkhar, Hartleb, et al., 2020). As different aquafeeds propose varying nutritional characteristics and are ultimately tested on varying species, the normalization of results based on protein inclusion (as the major consideration for fish meal and fish oil replacement strategies (De Silva & Anderson, 1994; Hua et al., 2019)) is expected to provide the most precise comparative results. Therefore, unit provision of protein is considered as the concentrated FU for comparisons in this study.

4.2.4. Quantification Methods

To provide a comprehensive impact assessment, all impact categories that are characterized by US EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) 2.1 are investigated. The conventional TRACI 2.1 impact categories (abbreviation, unit) are ozone depletion (OD, kg CFC-11 eq), global warming (GW, kg CO_2 eq), photochemical smog (PS, kg O_3 eq), acidification (AC, kg SO_2 eq), eutrophication (EU, kg N eq), human health carcinogenics (HHC, CTUh), human health non carcinogenics (HHNC, CTUh), respiratory effects (RE, kg $PM_{2.5}$ eq), ecotoxicity (EC, CTUe), and fossil fuel depletion (FF, MJ surplus). For each midpoint environmental impact category, the total amount of chemical emission or resource utilized is multiplied by its estimated potency. This methodology (TRACI 2.1) is reported to be based on the best available models and data in the US, allowing a desired level of comprehensiveness and accountability (Bare et al., 2012).

In addition to the conventional TRACI 2.1 impact categories, water intake (WI, Liters) and biotic resource use (BRU, kg C eq) are recognized as two important impact categories in food production processes, that are rarely investigated in aquaculture-related studies and LCA (Bohnes & Laurent, 2019; Lippiatt, 2007). For water intake, the Bees 4.0 tool is used in order to address the direct and indirect water resource use of processes (resource pollution is excluded in this impact category) (Lippiatt, 2007). For biotic resource use, calculations are performed based on the methodology described by Pauly and Christensen (1995) (Pauly & Christensen, 1995). For agricultural ingredients, the carbon content represented in the crop fraction of the plant is quantified (N Pelletier & Tyedmers, 2007). For ingredients derived from plants (e.g. concentrates and extractions), production yields were also assigned to obtain the proper impacts based on unit mass of dry matters. Biotic resource use for animal-based ingredients (fishery-derived or terrestrial) was calculated with the following formula:

$$P = \frac{m/x}{9} \, . \, 10^{(T-1)} \tag{1}$$

In which, P is the mass (g) of carbon appropriated, m is the mass (g) of animal-based ingredient, x is the animal-based ingredient production yield (mass of ingredient / mass of wet weight animal), and T is the trophic level of the organism. For the processes with multiple products, mass allocation is selected to assign appropriate impacts to each product.

These assessment methods follow the problem-oriented midpoint approach, which means that results are expressed in terms of their potential environmental impacts rather than actual damage levels (Nathan Pelletier & Tyedmers, 2010).

4.2.5. Feed Conversion Ratio (FCR)

An accurate assessment of feed intake is one of the most difficult aspects of the aquaculture industry to quantify (Glencross, Booth, & Allan, 2007), due in part to differences in nutritional requirements, such as fatty acids and carbohydrates, among different fish species (Oliva-Teles et al., 2015). However, the effect of diet on an aquatic species' growth and performance is an important principle that needs to be investigated. The efficiency of nutrient intake by animals is usually characterized as feed conversion ratio (FCR), which is calculated by the following equation:

$$Feed\ Conversion\ Ratio = \frac{1}{Feed\ Conversion\ Efficiency} = \frac{Consumed\ dry\ weight\ food}{Gained\ live\ weight\ product} \tag{2}$$

Typical FCRs for animal production (using commercial feeds and intensive production methods) are as follows: 6-10 for beef cattle, 2.7-5 for pork, 1.7-2 for poultry, and 1.0-2.4 for farmed fish and shrimp (Fry, Mailloux, Love, Milli, & Cao, 2018). Seafood production yields lower FCRs compared with other farmed terrestrial animals, indicating higher harvest yields for aquatic species. However, specific FCRs for seafood production depend on many factors such as diet type, species, and the harvesting environment characteristics.

4.2.6. Life Cycle Inventory: Aqua Diets

There are a large number of alternative feed ingredients that can be substituted for fish meal and fish oil, potentially leading to more sustainable formulations (Bell & Waagbø, 2008; Gatlin III et al., 2007; Nathan Pelletier, Klinger, Sims, Yoshioka, & Kittinger, 2018). Naylor et al., have classified these alternatives into the following groups: plant-based proteins/lipids, single cell protein/oils, rendered terrestrial animal products, and seafood by-products (Naylor et al., 2009). Following the aforementioned grouping approach, twelve different aquafeeds that have been successfully formulated and tested to produce seafood were extracted from the literature (to ensure practicality of diets usage). FMOC-1, FMOC-2, and FMOC-3 refer to the diets that are fish meal and fish oil containing with varying ingredients and protein content (42.3%, 41.0%, and 30.1% respectively) (Akiyama, 1990; Carter et al., 2003; John Davidson et al., 2016). FMF-1-T and FMF-2-T refer to the fish meal free diets, in which fish meal is replaced with terrestrial poultry by-product and terrestrial blood meal, respectively. Resulting protein contents are 38.5% for FMF-1-T, and 30.8% for FMF-2-T (El-Sayed, 1998; Rossi Jr & Davis, 2012). FMF-3-P and FMF-4-P refer to the fish meal free diets, in which fish meal is replaced with plant-based peanut meal and soybean meal, respectively. Resulting protein contents are 39.9% for FMF-3-P, and 38.5% for FMF-4-P (Adelizi et al., 1998). FMF-5-S refers to the forage fish meal free diet, in which fish meal is replaced with fish processing industry by-products. Resulting protein content is 34.0% (Ian Forster, Babbitt, & Smiley, 2004). FOF-1 and FOF-2 refer to the fish oil free diets, in which fish oil is replaced with vegetable (canola) oil, and both vegetable-based (canola) and single-cell protist-based (Thraustochytrid) oils (Byreddy, 2015; Carter et al., 2003). Resulting protein contents are 39.8 for FOF-1 and 39.1 for FOF-2 (Carter et al., 2003). Finally, FMOF refers to the fish meal and fish oil free diet, in which full replacement of fish meal and oil with terrestrial meal (poultry by-product), plant-based meal (mixed nuts), and seafood by-product (whitefish trimming) ingredients in undertaken. Resulting protein content is 42.2% (John Davidson et al., 2016). Summarized specifications regarding the aquafeeds nutritional characteristics, targeted animal (type and life stage), and the reported consecutive effects of feeding the aquafeed to animal (e.g. growth performance, water quality, etc.) are tabulated in Table 6. Additional specifications regarding the ingredients materials, amounts, corresponding LCI database, assumptions, and comments are provided in Tables B1-B12 of Appendix B.

Table 6. Summary of compiled formulated and tested aquafeeds.

Aquafeed	Study	Targeted Species	Life Stage	Pr%	FCR	Additional Specifications
FMOC-1	Davidson et al., 2016 (John Davidson et al., 2016)	Atlantic salmon (*Salmo salar*)	Post-smolt	42.3	0.90	FMOF diet resulted in higher TP, cBOD, and TSS** in the effluent compared to FMOC-1.
FMOC-2	Carter et al.,	Atlantic salmon *(Salmo salar)*	Pre-smolt	41.0	0.86	No significant difference in fish weight gain and feed consumption among FMOC-2, FOF-1, and FOF-2.

	2003 (Carter et al., 2003)					
FMOC-3	Akiyama, 1990 (Akiyama, 1990)	Carp	N/S*	30.1	2.10	Soybean meal is used to partially replace fish meal.
FMOC-4	Aas et al., 2019 (Aas, Ytrestøyl, & Åsgård, 2019)	Atlantic salmon *(Salmo salar)*	N/S*	35.6	1.21	This diet describes the average utilization of feed resources in salmon production in Norway during 2016. It includes all losses of feed and fish.
FMF-1-T	Rossi Jr. & Davis., 2012 (Rossi Jr & Davis, 2012)	Pompano *(Trachinotus carolinusL.)*	Juvenile	38.5	2.50	Fish meal is substituted with poultry by-product. Reductions in weight gain, feed efficiency, and protein and energy retention were observed compared to fish meal containing diets.
FMF-2-T	El-Sayed., 1998 (El-Sayed, 1998)	Nile tilapia *(Oreochromis niloticus L.)*	Fingerlings	30.8	2.60	Fish meal is substituted with blood meal. Reductions in fish performance (growth rate, protein efficiency) were noticed.
FMF-3-P	Adelizi et al., 1998 (Adelizi et al., 1998)	Rainbow Trout *(Oncorhynchus mykiss)*	Juvenile	39.9	1.21	Fish meal is substituted with peanut meal. Peanut meal replacement have resulted in lower weight gain and higher protein efficiency ratio.
FMF-4-P	Adelizi et al., 1998 (Adelizi et al., 1998)	Rainbow Trout *(Oncorhynchus mykiss)*	Juvenile	38.5	1.25	Fish meal is substituted with soybean meal. Soybean meal replacement have resulted in significantly higher weight gain and protein efficiency compared to commercial diet.
FMF-5-S	Forster et al., 2004 (Ian Forster et al., 2004)	Pacific white shrimp *(Litopenaeus vannamei)*	N/S*	34.0	1.33	Fish meal is substituted with Alaska fish processing industry by-products (primarily pollock). There were no significant difference in shrimp performance parameters (growth, FCR, survival) compared to the fish meal containing control diet.
FOF-1	Carter et al., 2003 (Carter et al., 2003)	Atlantic salmon *(Salmo salar)*	Pre-smolt	39.8	0.84	Fish oil is substituted with canola oil. No significant difference in fish weight gain and feed consumption among FMOC-2, FOF-1, and FOF-2.
FOF-2	Carter et al., 2003 (Carter et al., 2003)	Atlantic salmon *(Salmo salar)*	Pre-smolt	39.1	0.91	Fish oil is substituted with thraustochytrid and canola oil. No significant difference in fish weight gain and feed consumption among FMOC-2, FOF-1, and FOF-2.
FMOF	Davidson et al., 2016 (John Davidson et al., 2016)	Atlantic salmon *(Salmo salar)*	Post-smolt	42.2	0.89	FMOF diet resulted in higher TP, cBOD, and TSS** in the effluent compared to FMOC-1.

* Not Specified **TP: Total Phosphorus, cBOD: carbonaceous Biochemical Oxygen Demand, TSS: Total Suspended Solids.

The tabulated summary of varying diet aids to (a) acquire the environmental impacts levelized by protein provision (as a major nutrient necessary for aquatic species), (b) acquire the environmental impacts levelized by live-weight seafood production (as the proceeding output of aquafeed production), and (c) acknowledge the primary feeding characteristics used in the investigated studies.

4.2.7. Cost estimation for GW and BRU

Social cost of carbon (SC-CO_2) is an estimation of long-term economic harm (in dollars), which is caused by the impacts due to the emission of 1-ton carbon dioxide (CO_2) into the atmosphere. Despite the lack of precise information regarding the consequences of CO_2 emission, SC-CO_2 accounts for changes in net agricultural productivity, human health, property damages from increased flood risk, and changes in energy system costs, such as reduced costs for heating and increased costs for air conditioning. An estimation of $42 / ton of CO_2, in 2007 US$ (which equals $52 / ton of CO_2, in 2019 $US) is reported as SC-$CO_2$ for 2020, based on percent discount rate (D. P. Council, 2013). This value is used for comparisons and trade-off analysis in the discussion section.

Biotic resource use (BRU, as an estimation of net primary production use) is the amount of net flux carbon (biomass produced from photosynthesis) sequestered from the atmosphere to the system, in the sense of not being available for other purposes (Aubin et al., 2009; N Pelletier & Tyedmers, 2007). Richmond et al. estimated empirical prices for net primary production (based on the contribution of ecosystem services to GDPs) and assigned them to different nations (Richmond, Kaufmann, & Myneni, 2007). A price of $47 / 10^6 kg C, as 1996 US$ (which equals $77 / 10^6 kg C, as 2019 $US) is selected as the average of the range reported for the US estimated shadow price for net primary production (Richmond et al., 2007). This value is used for comparisons and trade-off analysis in the discussion section.

4.3. Results

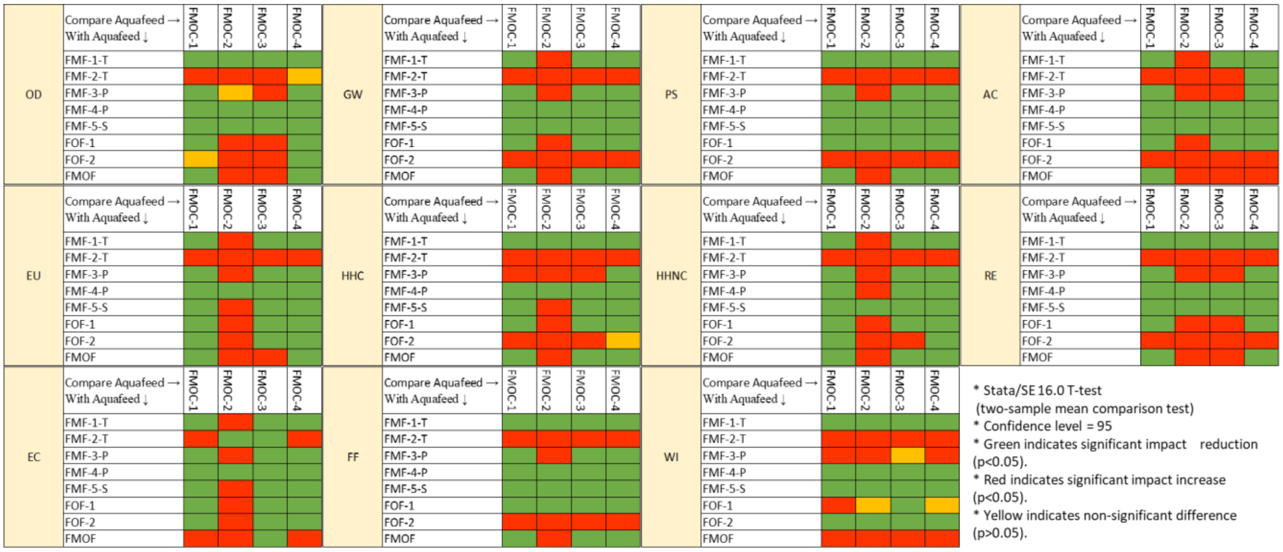
4.3.1. Aquafeeds Comparative Environmental Impacts

A quantitative assessment of 12 different aquafeeds formulations, attributed to each diet’s inputs and outputs is performed with 12 environmental impact categories. Relative results based on three FUs are illustrated in Figure 17. Absolute results are provided in Table S13 of the SI. For WI and all TRACI impact categories, t-test analysis based on 1 kg protein is also performed among FMOC diets vs alternative replacement diets (based on protein inclusion) to evaluate the significance of difference among investigated substitution alternatives. Summarized t-test analysis results are provided in Table 7. Expanded results regarding the Monte-Carlo simulation and t-test analysis are provided in Tables B14 to B25 and B29 of Appendix B.

Figure 17. Relative environmental impacts of aquafeeds based on (a) unit mass of aquafeed produced, (b) unit mass of protein inclusion, and (c) unit mass of live-weight seafood produced. Impact categories consist of OD, GW, PS, AC, EU, HHC, HHNC, RE, EC, FF, WI, and BRU. Different background colors indicate different formulation strategies (gray: fish meal and oil containing, pink: fish meal free, blue: fish oil free, green: fish meal and oil free).

As shown in Figure 17, considering any FU, none of the formulated feeds outperforms other aquafeeds for all investigated environmental impacts.

Table 7. Summarized results for the mean comparison t-test analysis (confidence level = 95) among FMOC diets vs. fish meal and fish oil replacement diets (based on 1-kg protein).



	Compare Aquafeed → With Aquafeed ↓	FMOC-1	FMOC-2	FMOC-3	FMOC-4
OD	FMF-1-T	🟩	🟩	🟩	🟩
	FMF-2-T	🟥	🟥	🟥	🟨
	FMF-3-P	🟩	🟨	🟥	🟩
	FMF-4-P	🟩	🟩	🟩	🟩
	FMF-5-S	🟩	🟩	🟩	🟩
	FOF-1	🟩	🟥	🟥	🟩
	FOF-2	🟨	🟥	🟥	🟩
	FMOF	🟩	🟥	🟥	🟩
GW	FMF-1-T	🟩	🟥	🟩	🟩
	FMF-2-T	🟥	🟥	🟥	🟥
	FMF-3-P	🟩	🟥	🟩	🟩
	FMF-4-P	🟩	🟩	🟩	🟩
	FMF-5-S	🟩	🟩	🟩	🟩
	FOF-1	🟩	🟥	🟩	🟩
	FOF-2	🟥	🟥	🟥	🟥
	FMOF	🟩	🟥	🟩	🟩
PS	FMF-1-T	🟩	🟩	🟩	🟩
	FMF-2-T	🟥	🟥	🟥	🟥
	FMF-3-P	🟩	🟥	🟩	🟩
	FMF-4-P	🟩	🟩	🟩	🟩
	FMF-5-S	🟩	🟩	🟩	🟩
	FOF-1	🟩	🟩	🟩	🟩
	FOF-2	🟥	🟥	🟥	🟥
	FMOF	🟩	🟥	🟩	🟩
AC	FMF-1-T	🟩	🟥	🟩	🟩
	FMF-2-T	🟥	🟥	🟥	🟩
	FMF-3-P	🟩	🟥	🟥	🟩
	FMF-4-P	🟩	🟩	🟩	🟩
	FMF-5-S	🟩	🟩	🟩	🟩
	FOF-1	🟩	🟥	🟩	🟩
	FOF-2	🟥	🟥	🟥	🟥
	FMOF	🟩	🟥	🟥	🟥
EU	FMF-1-T	🟩	🟥	🟩	🟩
	FMF-2-T	🟥	🟥	🟥	🟥
	FMF-3-P	🟩	🟥	🟩	🟩
	FMF-4-P	🟩	🟩	🟩	🟩
	FMF-5-S	🟩	🟥	🟩	🟩
	FOF-1	🟩	🟥	🟩	🟩
	FOF-2	🟩	🟥	🟩	🟩
	FMOF	🟩	🟥	🟥	🟩
HHC	FMF-1-T	🟩	🟩	🟩	🟩
	FMF-2-T	🟥	🟥	🟥	🟥
	FMF-3-P	🟥	🟥	🟥	🟩
	FMF-4-P	🟩	🟩	🟩	🟩
	FMF-5-S	🟩	🟥	🟩	🟩
	FOF-1	🟩	🟥	🟩	🟩
	FOF-2	🟥	🟥	🟥	🟨
	FMOF	🟩	🟥	🟩	🟩
HHNC	FMF-1-T	🟩	🟥	🟩	🟩
	FMF-2-T	🟥	🟥	🟥	🟥
	FMF-3-P	🟩	🟥	🟩	🟩
	FMF-4-P	🟩	🟥	🟩	🟩
	FMF-5-S	🟩	🟩	🟩	🟩
	FOF-1	🟩	🟥	🟩	🟩
	FOF-2	🟩	🟥	🟥	🟩
	FMOF	🟩	🟥	🟩	🟩
RE	FMF-1-T	🟩	🟩	🟩	🟩
	FMF-2-T	🟥	🟥	🟥	🟥
	FMF-3-P	🟩	🟥	🟥	🟩
	FMF-4-P	🟩	🟩	🟩	🟩
	FMF-5-S	🟩	🟩	🟩	🟩
	FOF-1	🟩	🟥	🟥	🟩
	FOF-2	🟥	🟥	🟥	🟥
	FMOF	🟩	🟥	🟥	🟩
EC	FMF-1-T	🟩	🟥	🟩	🟩
	FMF-2-T	🟥	🟩	🟩	🟥
	FMF-3-P	🟩	🟥	🟩	🟩
	FMF-4-P	🟩	🟩	🟩	🟩
	FMF-5-S	🟩	🟥	🟩	🟩
	FOF-1	🟩	🟥	🟩	🟩
	FOF-2	🟩	🟥	🟩	🟩
	FMOF	🟥	🟥	🟩	🟥
FF	FMF-1-T	🟩	🟩	🟩	🟩
	FMF-2-T	🟥	🟥	🟥	🟥
	FMF-3-P	🟩	🟥	🟩	🟩
	FMF-4-P	🟩	🟩	🟩	🟩
	FMF-5-S	🟩	🟩	🟩	🟩
	FOF-1	🟩	🟩	🟩	🟩
	FOF-2	🟥	🟥	🟥	🟥
	FMOF	🟩	🟥	🟩	🟩
WI	FMF-1-T	🟩	🟩	🟩	🟩
	FMF-2-T	🟥	🟥	🟥	🟥
	FMF-3-P	🟥	🟥	🟨	🟥
	FMF-4-P	🟩	🟩	🟩	🟩
	FMF-5-S	🟩	🟩	🟩	🟩
	FOF-1	🟥	🟨	🟩	🟨
	FOF-2	🟩	🟩	🟩	🟩
	FMOF	🟥	🟥	🟥	🟥

* Stata/SE 16.0 T-test
(two-sample mean comparison test)
* Confidence level = 95
* Green indicates significant impact reduction ($p<0.05$).
* Red indicates significant impact increase ($p<0.05$).
* Yellow indicates non-significant difference ($p>0.05$).

As shown in Figure 17 and Table 7, FMF-1-T presents comparable BRU relative to the FMOC diets (higher than FMOC-3, and lower than FMOC-1, FMOC-2, and FMOC-4). However, an overall improvement with respect to the other investigated indicators is assessed by shifting from FMOCs to FMF-1-T (reduction of impacts compared to all FMOC diets in 6/11 impact categories). FMF-2-T presents lower BRU relative to the FMOC diets. However, an overall increase of impacts with respect to the other investigated indicators is assessed by shifting from FMOCs to FMF-2-T (increase of impacts compared to all FMOC diets in 8/11 impact categories). FMF-3-P presents comparable BRU relative to the FMOC diets (higher than FMOC-3, and lower than FMOC-1, FMOC-2 and FMOC-4). Regarding the other investigated indicators, FMF-3-P presents comparable impacts relative to the FMOC diets. FMF-4-P presents comparable BRU relative to the FMOC diets (higher than FMOC-3, and lower than FMOC-1, FMOC-2 and FMOC-4). However, an overall improvement with respect to the other investigated indicators is assessed by shifting from FMOCs to FMF-4-P (reduction of impacts compared to all FMOC diets in 10/11 impact categories). FMF-5-S presents comparable BRU relative to the FMOC diets (higher than FMOC-3, and lower than FMOC-1, FMOC-2, and FMOC-4). However, and overall improvement with respect to the other investigated indicators is assessed by shifting from FMOCs to FMF-5-S. FOF-1 presents lower BRU relative to the FMOC diets. However, FOF-1 presents comparable impacts with respect to the other investigated indicators relative to FMOCs. FOF-2 presents lower BRU relative to the FMOC diets. However, an overall increase of impacts with respect to the other investigated indicators is assessed by shifting from FMOCs to FOF-2 (increase of impacts compared to all FMOC diets in 5/11 impact categories). FMOF presents comparable BRU relative to the FMOC diets (higher than FMOC-3, and lower than FMOC-1, FMOC-2, and FMOC-4). Additionally, FMOF presents comparable impacts with respect to the other investigated indicators relative to FMOCs.

Considering an overall reduction of BRU and an overall reduction of other environmental impacts as the primary and secondary objective of diets replacement, analyses indicate that FOF-1, in which fish oil is substituted with canola oil, is the best diet alternative (lower in BRU, comparable in other impacts). FMF-1-T, FMF-4-P, and FMF-5-S, in which fish meal is substituted with poultry by-product, soybean meal, and fish trimming by-product respectively, yielded other desirable alternatives to FMOCs (comparable in BRU, mainly lower in other impacts).

4.3.2. Contribution Analysis

To demonstrate which parameters contributed the most to impacts for each category and diet, a contribution analysis is performed. Results are summarized in Table 8.

Table 8. Relative contribution of aquafeeds ingredients to the total associated environmental impacts.

Diet \ Indicator	OD	GW	PS	AC	EU	HHC	HHNC	RE	EC	FF	WI	BRU
FMOC-1												
Legend:	■ Poultry Meal ■ Fish Meal ■ Fish Oil (menhaden) ■ Soy Protein Concentrate ■ Blood Meal ■ Canola Oil ■ Lysine-HCL ■ Other											
FMOC-2												
Legend:	■ Casein ■ Fish meal ■ Fish oil ■ Wheat Gluten ■ Cellulose ■ Canola oil ■ Bentonite ■ Other											
FMOC-3												
Legend:	■ Soybean meal ■ Fish meal ■ Fish oil ■ Wheat pollards ■ Rice bran ■ Methionine ■ Vitamin/Mineral premix ■ Other											
FMOC-4												
Legend:	■ Rapeseed oil ■ Fish meal (forage protein) ■ fish oil (forage) ■ Soy protein concentrate ■ Vegetable protein ■ fish oil (trimming) ■ Vitamins, minerals, amino acids ■ Other											
FMF-1-T												
Legend:	■ Poultry meal (by-product) ■ Soybean meal ■ fish oil (menhaden) ■ Corn starch ■ Whole wheat ■ Corn gluten meal ■ Choline-Cl ■ Other											
FMF-2-T												
Legend:	■ Blood meal ■ Wheat bran ■ Fish oil (sardine) ■ Corn starch ■ Alpha cellulose ■ Vitamin mix ■ Mineral mix ■ Other											
FMF-3-P												
Legend:	■ Peanut meal ■ Corn gluten meal ■ Fish oil (menhaden) ■ Corn gluten feed ■ Lysine ■ Methionine ■ Choline-Cl ■ Other											
FMF-4-P												
Legend:	■ Soybean meal ■ Corn gluten meal ■ Fish oil (menhaden) ■ Corn gluten feed ■ Yellow corn ■ Methionine ■ Choline-Cl ■ Other											
FMF-5-S												
Legend:	■ Fish meal (alaskan pollock trimming) ■ Minerals (phosphate) ■ Fish oil (menhaden) ■ Wheat starch ■ Whole wheat flour ■ Soybean meal ■ Brewers yeast ■ Other											
FOF-1												
Legend:	■ Fish meal ■ Mineral (Bentonite) ■ Casein ■ Wheat gluten ■ Canola oil ■ Cellulose ■ CMC (Carboxymethyl Cellulose) ■ Other											
FOF-2												
Legend:	■ Fish meal ■ Soybean meal ■ Casein ■ Wheat Gluten ■ Canola oil ■ Cellulose ■ Thraustochytrid meal ■ Other											
FMOF												
Legend:	■ Mixed nut meal ■ Poultry meal ■ Wheat flour ■ Fish oil (whitefish trimming) ■ Lysine-HCL ■ Choline-CL ■ Taurine ■ Other											

With respect to BRU, fish oil has the highest contribution of impact in all the diets that contain it as an ingredient (from either forage or trimming resources). For fish oil free diets (FOF-1 and FOF-2), fish meal has the highest contribution of impact.

With respect to the other investigated impacts, blood meal has contributed the highest to the impacts of FMOC-1, despite the higher quantity of other ingredients inclusion in this diet (e.g. fish meal and wheat flour). Blood meal also has the dominant contribution of impacts in FMF-2-T diet, in which fish meal is substituted with blood meal by design. Canola oil and bentonite (mineral) have contributed the highest to the FMOC-2 impacts. Soybean meal and rice bran were the top contributors of FMOC-3 impacts. For FMOC-4, rapeseed oil has the highest share to the overall impacts. Poultry meal and soybean meal were the highest contributors of impacts for FMF-1-T. For FMF-3-P, peanut meal and CGM (Corn Gluten Meal) have the highest portion of impacts. For FMF-4-P, soybean meal and CGM has contributed the most to the impacts. Minerals and wheat flour have revealed the highest contribution of impacts for FMF-5-S. Canola oil and minerals have resulted the most of impacts for FOF-1. For FOF-2, Algae-based Thraustochytrid meal has the overall highest contribution of impacts. Finally, poultry meal and mixed nut meal has contributed the highest to the overall impacts of FMOF.

Based on the aforementioned results from contribution analysis for FMOC diets, ingredients other than fish meal and fish oil have assessed to be the highest contributors of the environmental impacts in TRACI and WI impact categories (all except BRU). Therefore, the overall improvement for FMF-1-T, FMF-4-P, and FMF-5-S is due to either (a) relative lower impact of these diets high impact contributors (e.g. poultry meal, CGM, minerals, wheat flour, etc.) compared to the FMOCs high impact contributors or (b) relative lower inclusion of ingredients with high impact contributors, determined in FMOCs (e.g. soybean meal).

The overall increase of impacts for FMF-2-T (in all investigated impact categories except BRU) is attributed to the higher impact of blood meal compared to the FMOCs impact hotspots (e.g. canola oil, bentonite, rice bran, etc.). Further investigation into the blood meal process reveals that the high environmental impacts of blood meal in conventional impact categories are mainly due to the process' material-based inputs (chicken, pig, and beef co-products), which contribute to >82.8% of overall impacts in all TRACI impact categories (Table S26). CGM is another identified impact hotspot ingredient, recognized in both FMF-3-P and FMF-4-P. The high environmental impacts of CGM production in most of the conventional impact categories (all TRACI except PS) are mainly due to corn harvest and storage process (>77.18%, Table B27).

Finally, the overall increase of impacts in GW, PS, AC, RE, and FF for FOF-2 is due to (a) relatively high energy consumption for the production of single-cell protest-based thraustochytrid meal (Table S3) and (b) high contribution of electricity consumption (>85.5%) in the environmental impacts of thraustochytrid meal production in the aforementioned 5/12 impact categories (Table B28). Therefore, in order to prevent an increase of environmental impacts in impact categories rather than BRU (burden shifting), there is a demand to either (a) replace fish oil by a nutrient-equivalent oil (canola oil in the case studied) with relatively low energy consumption or (b) decrease the energy demand of algae-based oil production with comparable quantity of required nutrients (e.g. industrial optimization of thraustochytrid meal production).

4.4. Discussion

Burden shifting:

Despite the crucial importance of impact mitigation with respect to biotic resource depletion in the aquafeed industry, it is important to evaluate broader environmental impacts of aquafeed production using a comprehensive set of impact categories. This provides the opportunity mitigate unintended consequences of food production based on a systems thinking approach (Tlusty et al., 2019). The alternative fish meal free and fish oil free diets should not only perform better with respect to BRU (less impacts), but also should not pose additional environmental risks due to the elevated impacts in other impact categories. As shown in Figure 18, the reductions in the aquafeeds' BRU shadow price (from \$15.3, attributed to FMOC-1 to \$0.68, attributed to FOF-2) have not resulted in similar trend with respect to the social cost of carbon. In fact, SC-CO_2 is the highest for FOF-2 (\$1452.7), while this diet proposes the least BRU shadow price.

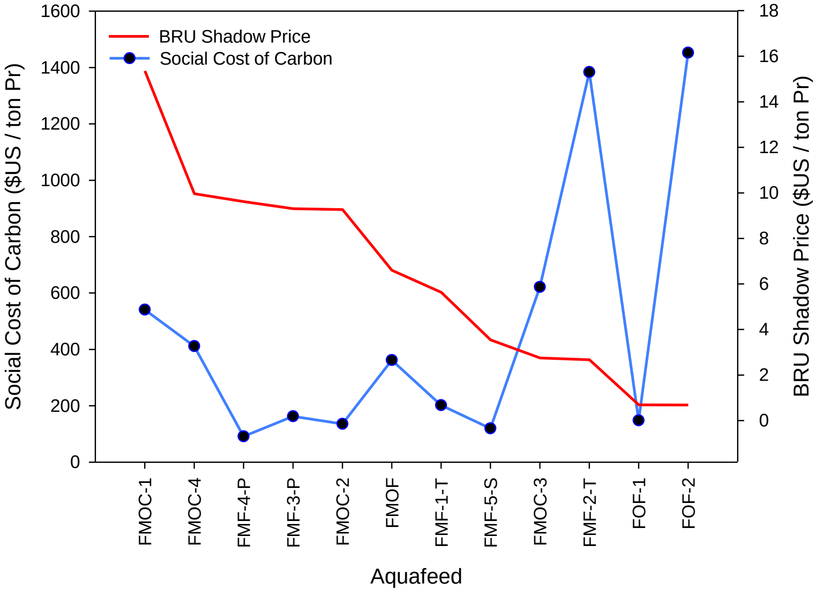


Figure 18. Relative social cost of carbon (left vertical axis) and BRU shadow price (right vertical axis) for different aquafeeds, levelized based on protein (Pr) inclusion. Prices are based on 2019 \$US.

In spite of the use of different monetary valuation methodologies and estimation criterion for SC-CO_2 and BRU, the comparison of trends and the order of magnitude for the estimated prices highlights the importance of exercising further caution in substituting ingredients to achieve alternatives with lower overall environmental impacts.

In-practice challenges:

In addition to environmental considerations for different aquafeeds, it is essential to investigate practical challenges that feed production industries might face when utilizing alternative ingredients. For example, by replacing marine-based ingredients with plant-based ingredients, the presence of anti-nutrients (compounds that reduce nutrients absorption from digestive system) are subject to increase the concentration of pollutants in the farming environment (Table 6) (John Davidson et al., 2016; Krogdahl, Penn, Thorsen, Refstie, & Bakke, 2010). Therefore, further purification efforts are required in the aquacultures using plant-based aquafeed alternatives to decrease total phosphorus (especially in dissolved form), carbonaceous biochemical oxygen, and total suspended solids. Moreover, replacement of fish meal and fish oil by seafood by-products is expected to increase the aquafeed's ash content (rich with calcium and phosphorus), which eventually causes zinc deficiency in aquatic species (Naylor et al., 2009; Shearer & Hardy, 1987). Therefore, implementation of zinc elevation steps is required in aquacultures using seafood by-products to mitigate the reductions in species growth and other performance characteristics (Z.-X. Song et al., 2017). Investigation of the economic challenges that the aquaculture industry is facing is another point of critical concern. High sensitivity of aquacultures' net revenue to the products' retail price is elaborated on previous studies (Quagrainie, Flores, Kim, & McClain, 2018; Xie & Rosentrater, 2015). Therefore, running aquaculture systems with the optimized operating costs (including the feeding diet) to ensure positive net revenue at varying products' retail prices is an important area of consideration in future. Future studies could conduct further investigations on methods and strategies to overcome practical seafood production challenges using fish meal free and fish oil free alternatives.

Other promising alternatives:

There are a variety of other promising alternatives that have been reported in the literature to potentially lead to more sustainable aquafeeds (Nathan Pelletier et al., 2018). These alternatives include krill, feather meal, and insect-based meal (e.g. soldier fly and house fly larvae). Krill is reported to be the most "underutilized" marine-based resource (due to cost and regulatory restrictions) (Naylor et al., 2009; Tou, Jaczynski, & Chen, 2007), that has the potential to be a high-quality protein resource (Katevas, 2014; Landymore, Durance, Singh, Singh, & Kitts, 2019). Feather meal, which is a co-product of poultry processing (Campos, Matos, Marques, & Valente, 2017), is reported to propose a high crude protein content (~86%) (Jasour et al., 2017; Nathan Pelletier et al., 2018). Black soldier fly and house-fly larvae is reported to be another highly promising alternative to provide sustainable protein, following the industrial ecology concept (feeding input from the growing animal agriculture waste)(Magalhães et al., 2017; Nathan Pelletier et al., 2018; Stull & Patz, 2019). Despite the inherent capability of these alternatives to fully or partly replace fish meal and fish oil in aquafeeds formulations, further research is required to understand (a) the required essential and semi-essential supplements that need to be integrated with the alternatives to obtain the optimized results in terms of products' quality and sustainability, and (b) the scale-up barriers for industrial aquafeeds production using the alternatives (Nathan Pelletier et al., 2018).

4.5. Conclusion

As current trends show an increasing desire towards aquafeeds production with the omission of ocean-based resources use (fish meal and fish oil), the present paper focuses on providing a broader perspective on fish meal and fish oil replacement strategies, considering a wide variety of relevant environmental indicators (impact categories).

A comprehensive analysis of the environmental impacts of aquafeed production is performed on 12 practically formulated and tested aquafeeds with different ingredient compositions, including fish meal and oil free diets. As the investigated diets have already been successfully utilized, their practicality is assumed to be promised. However, the environmental implications of investigated aquafeeds have been different in terms of resources use and pollutant emissions.

The major findings of this study are:

- ✓ Sole replacement of fish meal (no fish oil replacement) is potentially not effective enough to significantly reduce the use of biotic resources, but the replaced ingredients (poultry meal, soybean meal, and fish trimming by-product) can potentially lower the impacts based on other emission-based and resource-based indicators.
- ✓ Sole replacement of fish oil (no fish meal replacement) can potentially lead to significant decrease in the use of biotic resources. However, technologies regarding substitution methods needs to be improved in order to mitigate the energy use and its associated environmental impacts.
- ✓ In order to mitigate the overall environmental impacts of aquafeed production, considering biotic resources, abiotic resources and pollutant emissions, energy-efficient fish oil replacement strategies should be applied in addition to the fish meal replacement by alternatives with lower conventional environmental impacts.

4.6. Acknowledgement

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5. Chapter 5: Evaluation of Environmental and Economic Implications of a Cold-Weather Aquaponic Food Production System Using Life Cycle Assessment and Economic Analysis

This chapter was adapted from a submitted article, to be considered for publication with the anticipated citation of "Ghamkhar, R., Hartleb, C., Rabas, Z., Hicks, A. (2021). Evaluation of Environmental and Economic Implications of a Cold-Weather Aquaponic Food Production System Using Life Cycle Assessment and Economic Analysis." if accepted for publication.

By the time of finalizing this dissertation, the article appears as under review (after one round of revisions). Style and formatting modifications have been made for the purpose of this chapter preparation.

A holistic quantified environmental impact assessment of a cold-weather aquaponic system has been performed on chapter 2, to inform on potential approaches to elevate the environmental performance of the system. Here, evaluation of Economic implications, as another bottom line of sustainability, has been integrated with evaluating environmental implications of the investigated aquaponic system using three varying year-round production cycles. This provides the opportunity to leverage environmental and economic considerations together to propose strategies to improve aquaponic food production.

Authorship contribution statement

Ramin Ghamkhar: Designed Research, Performed Research, Analyzed Data, Wrote the Paper.

Christopher Hartleb: Provided Life Cycle Inventory Data, Revised the Paper, Provided Feedback.

Zack Rabas: Plotted Graphs, Provided Feedback.

Andrea L. Hicks: Designed Research, Provided Feedback, Wrote the Paper.

5.1. Introduction

Symbiotic integration of nutrient cycles is prospectively a sustainable food production strategy that mitigates waste and damages to ecosystems by implementing a closed loop circular approach (Delaide et al., 2017; Tibbs, 1992). Implementation of aquaponics, which are a combination of aquaculture and hydroponic systems, is one potential solution to reducing the adverse environmental impacts of aquaculture (e.g. eutrophication and water consumption) while maintaining the economic gains by adding to production types and quantities through symbiotic fish and plant growth (Boxman et al., 2017; Cohen et al., 2018; Xie & Rosentrater, 2015). As more products are generated and less waste is emitted per cycle of aquaponic production, combining these systems is anticipated to be a more environmentally and economically sustainable food production process compared to separate aquaculture-agriculture processes (Adler et al., 2000; Goddek et al., 2015; Xie & Rosentrater, 2015).

With respect to the environmental sustainability, many studies evaluated the environmental impacts of aquaponics (Bohnes et al., 2018; Cohen et al., 2018; Kalvakaalva, 2020; Maucieri et al., 2018; Somerville et al., 2014; X. Song et al., 2019; Wu et al., 2019). Cohen et al. (2018) found that combined aquaponic fish-vegetable production would result in significant reduction of impacts in eutrophication, water intake (water use), and geographic footprint (land use) environmental impact categories, compared to large-scale traditional non-integrated production (Cohen et al., 2018). Ghamkhar, Hartleb, et al. (2020) compared the environmental impacts for carnivorous cold-water fish production in an aquaponic system to conventional farm impact values and highlighted a notable reduction of impacts in acidification and eutrophication by aquaponic production. Despite the value of the current knowledge on the environmental impacts of aquaponics, there are three main gaps with respect to the environmental analysis of aquaponics: (a) The investigated impacts usually only cover a limited subset of the relevant environmental impact categories (Bohnes & Laurent, 2019; Wu et al., 2019), (b) The investigated systems are predominantly located in warm weather locations, in which heating and lighting requirements are relatively lower; and may not be representative to cold weather locations, in which heat requirements are relatively high (Wu et al., 2019), and (c) Applied alternatives to mitigate the environmental impacts of aquaponics are not fully explored within the studies (Ghamkhar, Hartleb, et al., 2020).

With respect to the economic sustainability of aquaponics, the body of literature is relatively limited with few successful commercial examples (Bich, Tri, Yi-Ching, & Khoa, 2020; Greenfeld, Becker, McIlwain, Fotedar, & Bornman, 2019; Love et al., 2014; Quagrainie et al., 2018). Chaves, Sutherland, and Laird (1999) compared the economic profitability of coupled catfish and tomato production in an aquaponic system with catfish production in a similar recirculating aquaculture system, and found that there is little difference in financial results at the margins budgeted (rate of return=27.32%). Tokunaga, Tamaru, Ako, and Leung (2015) investigated the economic feasibility of three aquaponic farms in Hawaii and revealed a slight economic benefit of a small-scale commercial aquaponic operation (rate of return = 7.36%). High variation of results among studies on aquaponic economic analysis is potentially due to variations in material and energy flows among different systems. Therefore, it highlights the importance of performing a case-specific economic evaluation of aquaponic food production in a cold-weather location.

In order to provide a holistic environmental-economic evaluation of aquaponic food production, life cycle assessment (LCA) and economic analysis (EA) were applied as quantification tools within the concept of industrial ecology (Bare et al., 2012; Garner & Keoleian, 1995; Konstantinidis et al., 2020). A holistic set of contributing parameters (inventory data), relevant environmental impact categories, and economic indicators were incorporated to provide a systematic perspective regarding aquaponic sustainability. Furthermore, major contributors were identified in order to determine the next steps to improve the environmental and economic sustainability of aquaponic food production (X. Song et al., 2019).

This work used LCA and EA to provide a comparative environmental and economic evaluation of a research-scale, cold-weather aquaponic system (US-Midwest), which cultivated varying aquatic species in different years along with varying vegetables. A holistic set of environmental impact categories (10 impact categories) and economic indices (4 indicators) were employed to determine major contributing parameters and potential strategies to enhance environmental and economic favorability of the aquaponic food production system.

The paper was organized as follows: methods (section 5.2) consisted of, system description (5.2.1), goal and scope definition (5.2.2), and life cycle inventory (5.2.3). Afterwards, results for this analysis were organized in section 5.3. Section 5.3.1 covered the environmental impact assessment and sensitivity analysis of the investigated system under different treatments. Section 5.3.2 explained the economic analysis results and the contribution of different factors in the economic performance of the aquaponic system. Further discussions regarding the results of this study as well as potential future research based on the outcomes were made in section 4. Finally, conclusions were presented in section 5.

5.2. Methods

5.2.1. System Description

A combination of six identical, entry-level aquaponic systems, each consisting of two fish tanks, two clarifiers, two mineralization tanks, one communal bioreactor/degassing tank, four rafts, one sump tank, one heater, one water pump, one air pump, covering nets, 144 rockwool cubes, and four light bulbs and fixtures were used in the investigation. A simplified overview of the infrastructure parameters for the aquaponic system was illustrated in Figure 19. The system's operation was investigated for three different annual production cycles (2015, 2016, and 2017) to produce vegetables (butterhead lettuce (*Lactuca sativa* L.), Romaine lettuce (*Lactuca sativa* L. var. longifolia), pak choi (*Brassica rapa)*, and kale (*Brassica oleracea* var. sabellica)) along with tilapia (*Oreochromis niloticus*), conventional walleye (C-walleye, *Sander vitreus*), and hybrid walleye (H-walleye, *Sander vitreus x Sander canadensis*), respectively. Each analyzed scenario represented one year of production.

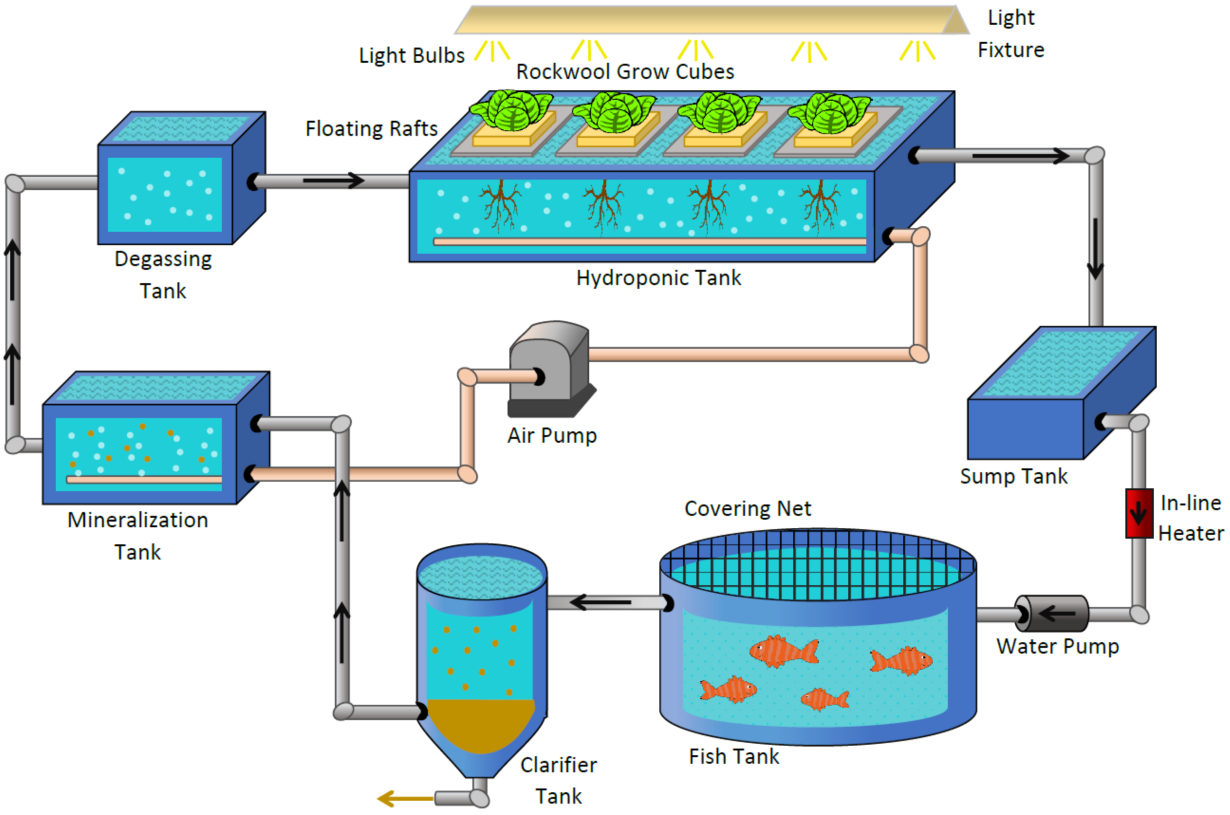

Figure 19. Simplified overview of the aquaponic system (quantities of each component is excluded). Arrows within the pipes indicate the water flow direction.

In each aquaponic system, fish were fed with a commercially available dry feed with the protein and nutrients required by each fish type. Consequently, the excreted waste contained dissolved nutrients, such as ammonia (NH_3), as a product of fish metabolism. The nutrient rich water were directed to the clarifiers to remove most of the solids waste. By means of nitrification and mineralization, NH_3 was oxidized into nitrite (NO^{2-}) and then nitrate (NO^{3-}), which was less harmful for aquatic species, and provided the essential macro- and micro-nutrients for the plants. After degassing, the nutrient-containing water was directed to the raft tanks, where the plants consumed the inorganic ions through nutrient uptake. Finally, water was directed to the sump tank, which acted as a controller for water level fluctuations in raft and fish tanks.

5.2.2. Goal and Scope Definition

The main goal of this study was to determine the environmental and economic implications of a cold weather aquaponic food production system, located in the Midwestern US. The investigated system included a comprehensive set of processes and factors that posed associated environmental impacts and economic considerations.

5.2.2.1. System Boundary

The final product of the system was food for human consumption (in terms of fish and plants) at the aquaponic "gate"; this study was a cradle-to-gate assessment. Post-farm processes (e.g. packaging, transportation, distribution, use, end of use) were excluded from the scope of this assessment due to the lack of reliable data and potential variation in post-farm scenarios (Ghamkhar, Hartleb, et al., 2020). To incorporate the multi-functionality of the aquaponic system, mass allocation was selected to partition the environmental impacts to both co-products (fish and plants) (Hindelang et al., 2014). The functional unit for the midpoint impact assessment was considered as the impact per kilogram of live-weight fish (product) produced annually in the research-scale aquaponic system, due to the intended function of the system as fish production.

5.2.2.2. Evaluation Criteria: Environmental

LCA is a standardized method conceived to assess the environmental impacts associated with a product or process (Berardy, Seager, Costello, & Wharton, 2020). According to the International Standard Organization guidelines (ISO14040-14044), LCA is comprised of four steps: goal and scope definition, inventory, impact analysis and results interpretation (ISO-Norm, 2006; Wu et al., 2020). In the goal and scope definition, the motivation of performing LCA, product system boundary, functional unit, and data parameters is defined (Hicks, Temizel-Sekeryan, Kontar, Ghamkhar, & Morris, 2020). In the inventory stage, resources consumed and emissions to the environment at all stages of a process's lifespan, from the raw material extraction to the disposal of waste, are quantified (Guinée, 2002; ISO, 1997). In the impact analysis step, identification and evaluation of key issues are made. In the end, recommendations and conclusions are made in an interpretation step (Lee & Inaba, 2004).

SimaPro 8.2.0 was used for the LCA as the modeling platform, using databases from Agri-footprint (Durlinger et al., 2014), Ecoinvent-3 (EcoInvent, 2014), European reference Life Cycle Database (ELCD) (Goedkoop et al., 2008), and United States Life Cycle Inventory (USLCI) (Norris, 2004) databases.

To provide a holistic impact assessment, multiple impact categories, which are characterized by US EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) 2.1, were investigated. The included TRACI 2.1 midpoint environmental impact categories (abbreviation, unit) were ozone depletion (OD, kg CFC-11-eq), global warming (GW, kg CO_2-eq) (time horizon: 100 years), photochemical smog (PS, kg O_3-eq), acidification (AC, kg SO_2-eq), eutrophication (EU, kg N-eq), human health carcinogenics (HHC, CTUh), human health non carcinogenics (HHNC, CTUh), respiratory effects (RE, kg $PM_{2.5}$-eq), ecotoxicity (EC, CTUe), and fossil fuel depletion (FF, MJ surplus). For each environmental impact category, the total quantity of chemical emission or resource utilized was multiplied by its estimated potency. This methodology (TRACI 2.1) is reported to be based on the best available models and data in the US, which allows a desired level of comprehensiveness and accountability (Bare et al., 2012). For all investigated impact categories, Monte Carlo simulations in SimaPro 8.2.0, for 1000 runs to the 95th confidence interval was performed in order to visualize and estimate the total variations in output parameters (Tables C10-C12 of the Appendix) (von Brömssen & Röös, 2020). These assessment methods followed the problem-oriented midpoint approach, which means that results were expressed in terms of their potential environmental impacts rather than actual damage levels (Nathan Pelletier & Tyedmers, 2010).

5.2.2.3. Evaluation Criteria: Economic

Year-round operation of the investigated aquaponic system (located at University of Wisconsin-Stevens Point Aquaponic Innovation Center) was investigated to account for different aquatic species produced at different years. Tilapia, C-walleye , and H-walleye were produced along with different vegetables during 2015, 2016, and 2017, respectively. Tabulated and categorized set of infrastructure costs, operating costs, and revenues for the investigated aquaponic system was provided in Tables C4-C8 of Appendix C.

Compiling the financial parameters associated with the aquaponic system operation under different conditions (e.g. produced species, heating requirements, etc.) provided the opportunity to use financial indices to perform a comprehensive economic analysis. The financial tool indices used in this study were Net Present Value (NPV, aka Net Present Worth) (Nagalingam, 1999), Internal Rate of Return (IRR) (M. T. Chen, 1998), Payback Period (PBP) (Wildern, 1997), and Benefit to Cost Ratio (BCR) (Shively & Galopin, 2013). An annual interest (discount) rate of 10% (Rupasinghe & Kennedy, 2010), and a 20-year operation horizon (Ghamkhar, Hartleb, et al., 2020) was considered for the calculations. Detailed explanation on the methodology and inventory regarding economic indices was provided in Tables C4-C8, and economic analysis methods section in appendix C.

5.2.2.4. Evaluation Criteria: Sensitivity and Contribution Analysis

To quantitatively identify the input and output parameters to which the results of the investigated system were sensitive (with corresponding changes in the impact results), a complementary sensitivity analysis was performed for all environmental indicators and production cycles. For each parameter listed in the inventory, the value was modified by ± 20%. The updated impacts of the existing system was re-calculated to determine how the change in input affected the impacts for each indicator or impact category. The relative change of the output terms was compared with the relative change of the input terms to calculate the sensitivity factor (SF). For any given parameter, if the calculated sensitivity factor (SF) was less than 0.1 for all impact categories, the sensitivity of final output to that parameter was considered as negligible (non-sensitive parameter). For complementary economic analysis, contribution analysis was selected to be performed rather than sensitivity due to two main reasons: (1) Illustration of the economic contribution results provided a simplified glance with similar conclusions; (2) As opposed to environmental impact categories, which were representing different indicators, economic indices explained and compared the favorability of the system cycles in one aspect, which was fiscal performance. To perform contribution analysis, all parameters were fragmented and expressed in terms of net present costs (NPCs). The contribution of each parameter to the overall systems' net present cost (NPC=-NPV) was considered as the parameter's contribution to the overall economic performance.

5.2.3. Life Cycle Inventory

To conduct a holistic assessment, a comprehensive set of material and energy inputs and outputs was compiled from all three production cycles (2015, 2016, and 2017). The incorporated parameters were inputs (electricity, heat, aquafeed, seeds, infrastructure, fingerlings, water, and labor) and outputs (fish, plants, and solids waste). Figure 20 demonstrated the flow diagram of the aquaponic system investigated in this study.

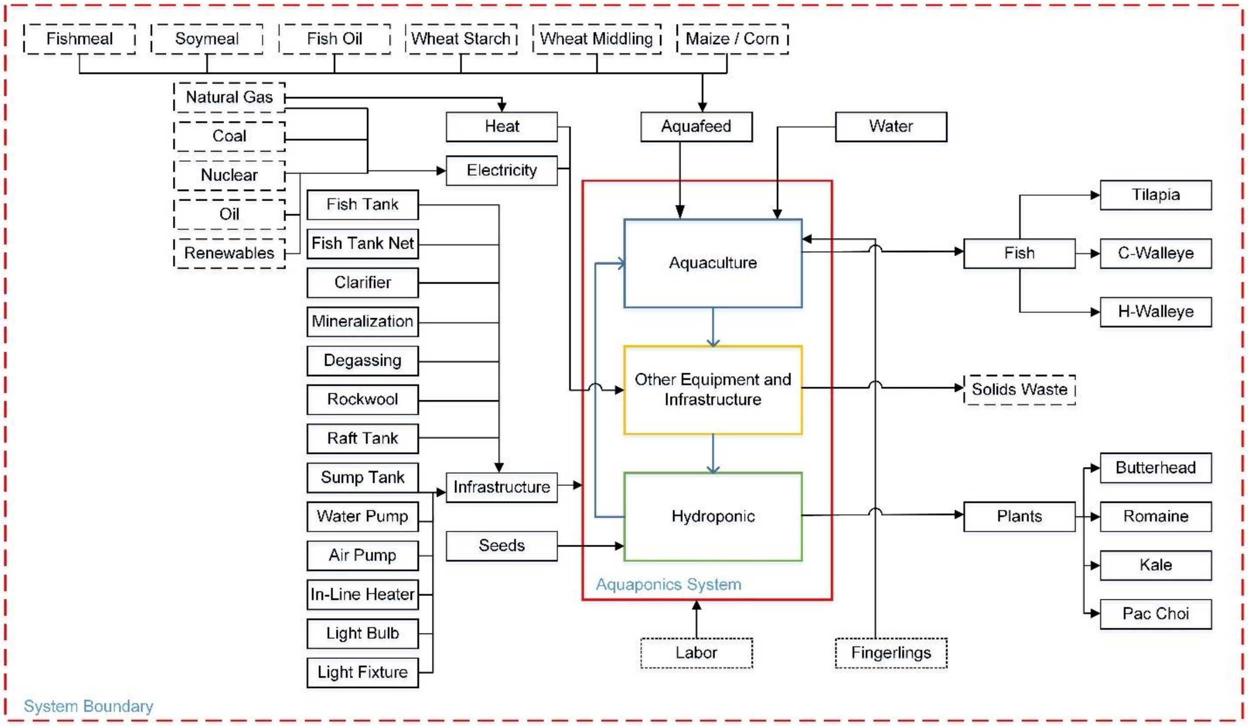

Figure 20. Materials and energy flow diagram and system boundaries of the aquaponics system. Dashed boxes indicate parameters that are expanded for LCA. Dotted boxes indicate parameters that are expanded for EA. Blue Arrows indicate the water flow within the aquaponics system, while black arrows indicate materials and energy inputs/outputs within the system boundary.

5.2.4. Assumptions

The annual water consumption was assumed to be constant among different operation years as a result of: (1) Indoor greenhouse temperature, pressure, and relative humidity was kept unchanged over three production years (P=1atm, T= 23℃). Therefore, the vaporization flux and consequent make-up water requirement was constant. (2) System equipment and infrastructure was not changed over the investigated years. Thus, the initial fill-in water requirement was also constant. In spite of similar pumping and lighting requirements for the system throughout different years, the rearing species have different temperature tolerance ranges, posing varying in-line heating and chilling demands. Accordingly, the utility data for different production years was used to acquire system's electricity usage. The electricity sources were selected based on the provider's resource fractions (38% natural gas, 37% coal, 4% oil, 21% renewables (*2017 Corporate Sustainability Report - Alliant Energy*, 2017)). Space heating demand changed for different production cycles, simply because the atmospheric temperature conditions varied across the investigated years, requiring different heating to keep the indoor temperature constant at 23 ℃. The overall final quantity of vegetables produced was dissimilar across different years due to the nutrients availability (nitrogen phosphorus, etc.) in the circulating flow, the operators' experience in hydroponic cultivation, and the species of fish produced. As the overall amount of generated solid waste were not available for two (out of three) production years, the ratio of solid waste / mass run off (mass of feed – mass of produced fish) is assumed to be constant over different production cycles (≈ 0.35) to calculate the estimated solids waste generated.

5.3. Results

5.3.1. Environmental Implications

A quantitative environmental impact assessment of the aquaponic food production process, attributed to the system inputs and outputs according to different operational conditions (tabulated in Table S1-S3 of the SI) utilizing mass allocation over a one-year process, was performed. Results based on one kg production of live-weight of fish were illustrated in Figure 21.

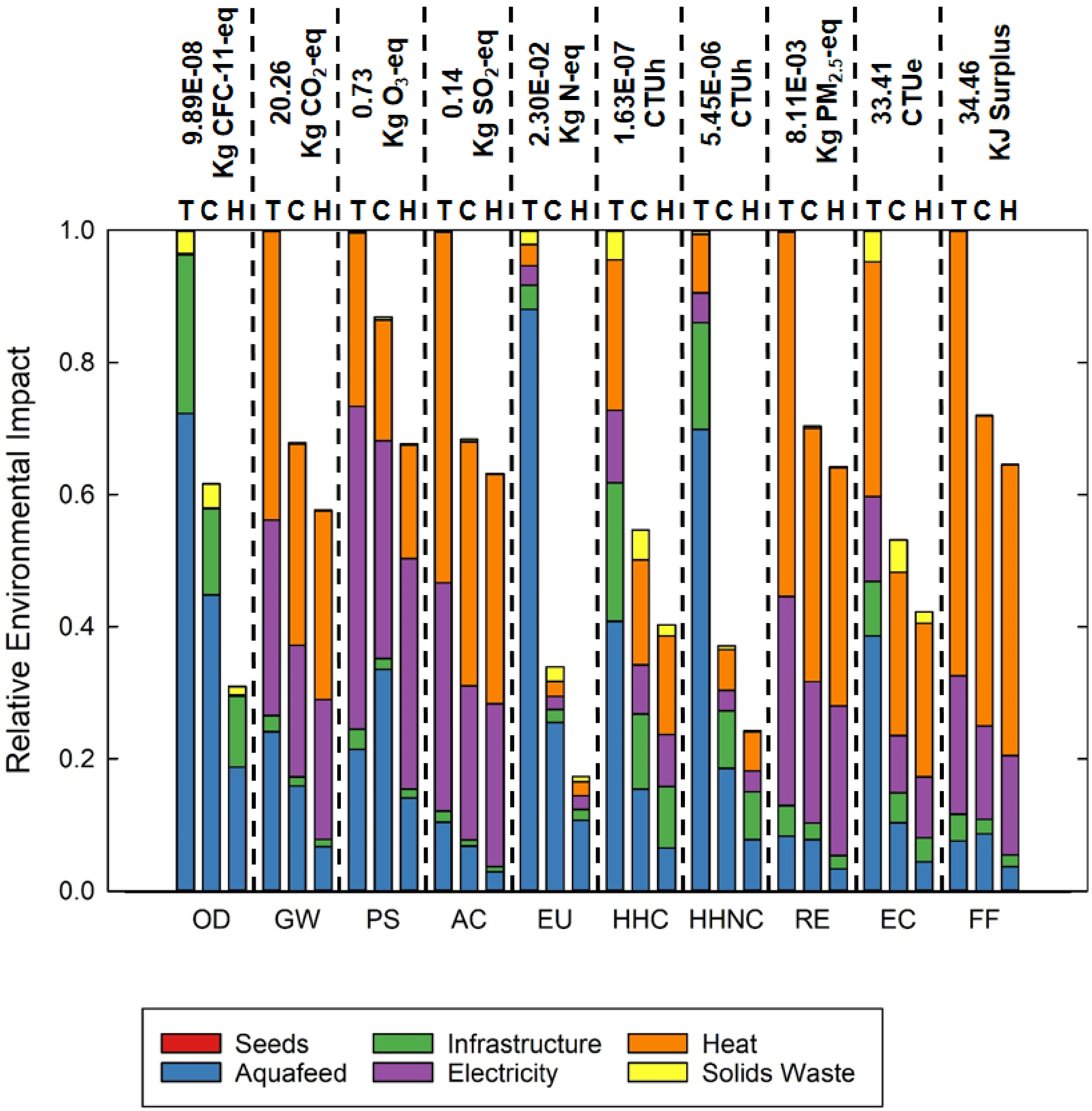

Figure 21. Relative Environmental Impacts of the aquaponics system year-round operation per kg of live-weight of fish produced: results for 2015 (tilapia production, T), 2016 (C-walleye production, C), and 2017 (H-walleye production, H). Numbers on the upper bar represent the quantified environmental impact value of the top 1 in each category.

With respect to all TRACI impact categories for all production years, more than 90.7% of total environmental impacts were attributed to four parameters: aquafeed, infrastructure, electricity, and heat. These parameters represent the impact hotspots in the aquaponic system analysis (Ghamkhar, Hartleb, et al., 2020).

For all impact categories, the quantified environmental impacts were following the order of T (2015, tilapia) > C (2016, C-walleye) > H (2017, H-walleye), despite the elevated energy demands throughout the years (heat + electricity) due to temperature variations. As aquafeed demands and waste generation have been increasing from T to C and decreasing from T to H, the reduced environmental impacts were due to the increase in the amount of final product (fish + plants), due to more efficient operation of the system through the years. As the total amount of produced live-weight fish was reduced from T to C and H (since fry walleye weigh ~200 g less than tilapia), the overall increase in final products' mass was attributed to elevated plants production. This was in line with the findings of Love et al. (2015), and highlighted the importance of system operation experience, specifically regarding plant production, to elevate system outputs and consequently elevate systems environmental performance per unit of product.

Quantified impact results from this study were compared to other fish and animal production methods (e.g. net pen aquaculture, beef, etc.). A summary of the results for GW and EU (per live-weight product) was tabulated in Table 9. Despite different scopes and characterization methods for different LCA studies, comparison of impacts difference of magnitude helped to have a better understanding of the system's environmental performance compared to other food production systems (Guzmán-Luna, Gerbens-Leenes, & Vaca-Jiménez).

Table 9. Comparison of global warming (GW) and eutrophication potentials (EU) resulted from this study and other food production systems (recirculating aquaculture, net pen aquaculture, beef, poultry).

System Type	Aquaponic	Aquaculture (recirculating)	Aquaculture (net-pen)	Beef	Poultry*
Impact Category	This Study	Aubin et al. (2006)	Nathan W Ayer and Tyedmers (2009)	Ogino et al. (2016)	Williams, et al. [41]
Global Warming (kg CO_2-eq/kg live-weight)	11.67 - 20.26	6.02 - 10.64	2.07	10.6 - 14.0	4.58
Eutrophication (kg N-eq/kg live-weight)	0.39E-02 - 2.30E-02	14.55E-02 - 18.01E-02	3.53E-02	7.11E-02 - 7.93E-02	11.47E-02

* Quantified impacts for this system are based on the functional unit of carcass dead weight.

As shown in Table 9, the resulting EU impacts from the investigated system in this study were lower than other production systems (aquaculture: recirculating and net pen, beef, poultry) by ~1 order of magnitude. This was mainly due to the internal use of micronutrients (N and P) within the aquaponic system instead of emitting them to the environment. However, the resulting GW impacts from the investigated system was either slightly higher or at the same level compared to other analyzed food production systems. Looking at the systems environmental impact contributors to GW (as well as the sensitivity analysis results, which was further explained in the next section), heat was a major contributor of the GW impacts for all investigated production cycles. The elevated heating demands for the investigated aquaponic was expected due to the location of the system (cold weather climate). However, in a hypothetical scenario that heating requirements were neglected, the GW impacts of the aquaponic system would reduce to 5.7 to 11.4 kg CO_2-eq, which was a slightly lower range compared to the analyzed aquaculture (recirculating) and beef production. Considering the mitigation of impacts regarding other environmental indicators (e.g. EU) (Ghamkhar, Hartleb, et al., 2020), expected economic gains due to multi-functionality of aquaponics (further investigated in the next sections) (Blidariu & Grozea, 2011; Tsakiridis, O'Donoghue, Hynes, & Kilcline, 2020), and the elevation of food systems resiliency via local production (Turnšek et al., 2019), implementation of aquaponics food production is still a potential sustainable approach. However, strategies to reduce the environmental impacts of such setups in cold-weather environments regarding global impact categories (such as GW) need to be analyzed and executed.

5.3.1.1. Sensitivity Analysis

To quantitatively evaluate the overall sensitivity of final economic evaluation results with respect to the initial investment parameter (infrastructure cost, operating costs, and total revenues), sensitivity analysis was performed. Sensitivity factors (SFs) were calculated as |Percentage of change in final NPV| / |Percentage of change in the input parameter|, and illustrated in the Figure 22.

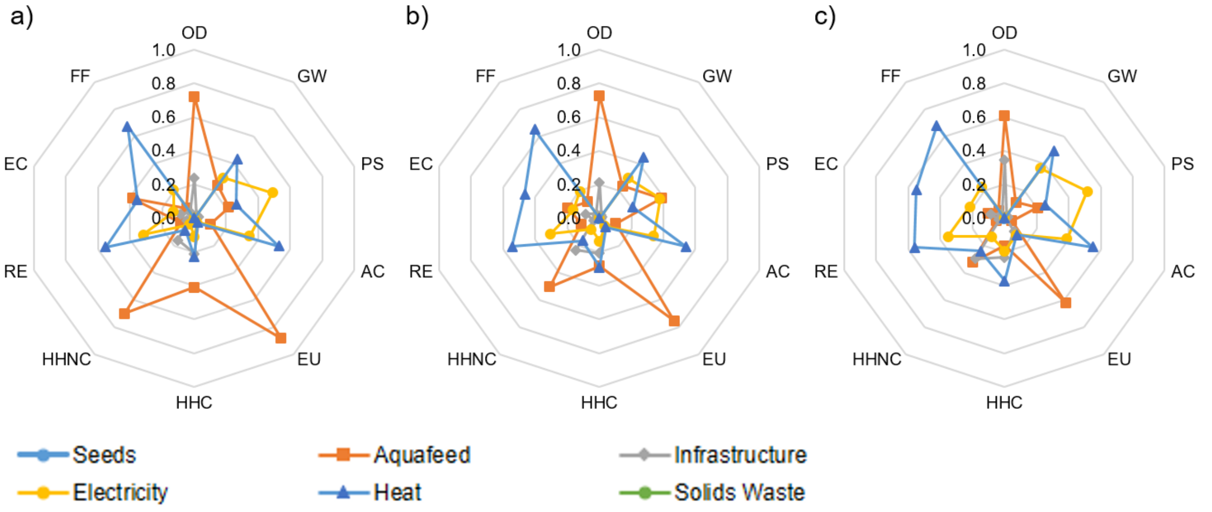

Figure 22. Sensitivity Factors (SFs) for the contributing parameters regarding TRACI impact categories for (a) 2015, tilapia production, (b) 2016, C-walleye production, and (c) 2017, H-walleye production.

For all production cycles, seeds and solids waste posed negligible SFs (<0.1 for all impact categories). Contrarily, aquafeed, heat, electricity, and infrastructure resulted to the highest sensitivity factors in the investigated impact categories consecutively. With respect to GW, AC, RE, and FF, heat was identified as the most sensitive parameter (SFs = 0.4, 0.5, 0.5, 0.6, respectively). Therefore, the environmental impact mitigation of the cold-weather located system for the aforementioned impacts, which included 4 out of 10 indicators, was most efficient by reducing the impacts associated with heat (e.g. effective space heating, insulation, etc.). With respect to OD, EU, and HHNC, aquafeed was shown to be the most sensitive factor (OD SFs= T: 0.7, C: 0.7, H: 0.6; EU SFs= T: 0.9, C: 0.7, H: 0.6; HHNC SFs= T: 0.7, C: 0.5, H: 0.3).

Therefore, the mitigation of OD, EU, and HHNC environmental impacts, which incorporated 3 out of 10 indicators, was most efficient by reducing the environmental impacts of the aquafeed that was used in the production system. For example, systems in the locations that are linked to eutrophication (EU) issues could prioritize aquafeed environmental performance improvement (e.g. nutrient uptake improvement, more sustainable ingredient replacements, etc.). Regarding PS, electricity was shown to be the most sensitive factor (SFs= T: 0.5, C: 0.4, H: 0.5). Therefore, mitigation of PS impacts associated with the aquaponic system was most effective when mitigating the impacts associated with electricity consumption (e.g. renewable electricity grid, efficient use of natural lighting, etc.). This highlighted the importance of elevating clean electricity consumption, especially for urban regions, where photochemical smog is a problem. For HHC and EC impact categories, either heat or aquafeed posed the most SFs among all contributing parameters. This indicated the importance of considering both of the aforementioned parameters for the mitigation of system's environmental impacts regarding toxicity to the environment (EC) and carcinogenicity to humans (HHC). Despite the traditional assumption of negligible infrastructure impacts (Nathan W Ayer & Tyedmers, 2009; Ghamkhar, Boxman, et al., 2020), the sensitivity analysis of the investigated aquaponic system indicated that the infrastructure could pose a relatively high SF, especially regarding OD, HHC, and HHNC. This emphasized the importance of not neglecting infrastructure and incorporating this parameter within the system boundary in future studies.

5.3.2. Economic Implications

An economic analysis of the aquaponic system operation under different conditions at different years was performed. The financial parameters associated with the aquaponic system operation was compiled in Tables C4-C8 of Appendix; and the utilized financial indices to perform a comparative economic assessment (NPV, IRR, PBP, and BCR) were explicated in section 8 of the SI. The cash flow results with respect to the different processing conditions were tabulated in Table 10. As shown in Table 10, results indicated an economic gain based on C-walleye and H-walleye (2016 and 2017) production data, and an economic loss based on tilapia (2015) production data for the investigated aquaponic system. Results based on all indices showed the best financial return on investment for the 2017 production, where H-walleye were produced (highest NPV, IRR, BCR and lowest PBP).

Table 10. Financial analysis results for the aquaponic food production

Financial Indicator	2015: Tilapia Production	2016: C-Walleye Production	2017: H-Walleye Production
NPV	-$108,785	$35,366	$167,369
IRR	N/A*	22%	62%
PBP	N/A*	3.96	1.49
BCR	0.47	1.16	1.75

*N/A: Not Applicable; net cash flows for all years are negative within the lifespan (net costs>net benefit).

By comparing tilapia to walleye production (conventional and hybrid), it was observed that both operating costs and net revenues were increasing. The increase in the operating costs (cash outflows, Δ (NPV) ≈ -$16K) was mainly attributed to the higher energy requirements for walleye production cycles (C, 2016 and H, 2017) compared to tilapia production cycle (T, 2015). However, the overall positive cash flow differentiation (cash inflows, Δ (NPV) ≥ $159K) outweighed the overall negative cash flow differentiation (Δ (NPV) ≈ $16K) by adding on the net fish and plant revenues for walleye production cycles, comparing to tilapia production cycles. The relative favorability of H-walleye production compared to C-walleye production was attributed to elevated revenues for H-walleye production cycle (Δ (NPV) ≥ $133K) despite similar infrastructure (Δ (NPV) = 0) and operating Δ (NPV) < $2K) costs. The economic indices utilized in this study on a real-case aquaponic food production system indicated that the practical enhancement of return on investment was dependent on optimization of both cash inflows and outflows (neither could be neglected).

In sum, economic analysis of the investigated aquaponic system revealed that neither of the overall associated benefits or costs could be neglected to achieve elevated net economic profits. However, a detailed evaluation of benefit and cost contributors (contribution analysis) was needed to be performed to obtain precise insights regarding the investigated aquaponic economic implications, and the contributing parameters.

5.3.2.1. Contribution Analysis

The initial assessment of the economic results highlighted the importance of considering both cash inflows and outflows in the economic assessment of the aquaponic system. However, it did not provide the relative and absolute economic contribution of each parameter. To recognize the economic implications associated with each material and energy based parameter (in line with what developed earlier for the environmental implications), a contribution analysis based on net present values (i=10%, t=20 yrs.) was performed (Table S9 of the SI). Results were illustrated in Figure 23.

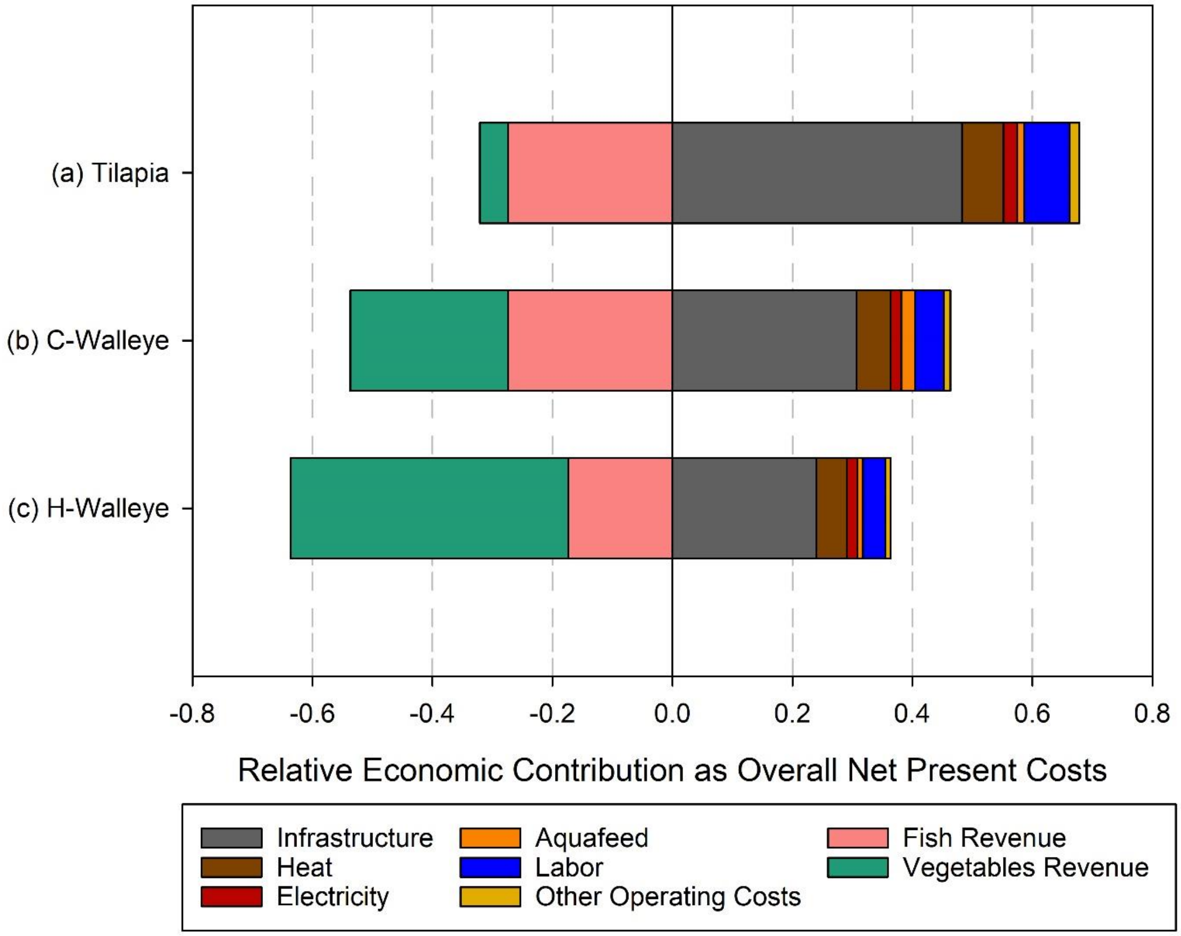

Figure 23. Economic Contribution Analysis for (a) Tilapia (2015), (b) C-Walleye (2016), and (c) H-Walleye (2017) production cycles. Results are harmonized based on infrastructure costs, operating costs, and revenues net present values over the systems lifetime (20 years).

With respect to the system costs, three parameters contributed to > 88% of overall costs for all production cycles, which were infrastructure, heat, and labor. In fact, > 66% of system's costs was attributed to the infrastructure. This highlighted the importance of minimizing infrastructure costs to improve the overall economic performance of the aquaponic system. Grouping infrastructure costs into (1) initial non-replacing (e.g. tanks that are used over the full lifetime) and (2) replacing (e.g. water pumps that are replaced every 7 years) helped to identify prospective steps to minimize infrastructure costs. The initial non-replacing factors resulted to an NPV ≈ $15K, while the replacing factors resulted to an NPV ≈ $132K. This indicated that the replacing factors contributed 9 times more to the overall costs resulted from infrastructure, compared to non-replacing factors. Improving replacing factors lifespan (e.g. use of more durable lightbulbs, pumps, and in-line heater/chillers) could potentially reduce the overall infrastructure costs.

With respect to the system revenues, both fish and vegetables posed a relatively significant contribution to the net system's revenue (at least 14% and 27% respectively). In fact, the overall increase of fish and plants production for walleye cycles compared to the tilapia cycle resulted a transition of net negative net revenue to net positive net revenue, despite the increased operating costs (Table 10).

Similar to what found earlier regarding system's environmental performance, the elevated co-production of plants from 2015 to 2016 (Δ NPV from plants ≈ \$112K), and from 2016 to 2017 (Δ NPV from plants ≈ \$158K) was significantly contributing to the improvement in system's economic performance (summarized in Table 10). Comparing C-walleye (2016) production cycle to H-walleye production cycle, an elevated net economic gain was obtained (Δ NPV ≈ \$132K) despite lower gain from fish production (Δ NPV from fish ≈ -\$25K). However, the increased production of plants had outweighed the decreased production of fish. The large range of plant production quantity from three production cycles, and its significance of effect on the total system's revenue (14% for 2015,T; 72% for 2017, H) highlighted the importance of optimizing co-production of plants (e.g. improving operators experience for hydroponic cultivation, selection of most compatible plants, etc.) to elevate aquaponic system economic performance.

Leveraging the hotspot inputs from environmental (heat, aquafeed, electricity, infrastructure) and economic (infrastructure, labor, heat) evaluations, the analyses indicated that heat and infrastructure were the two input parameters that need to be prioritized for further investigation to enhance the aquaponic operation favorability, both in terms of environmental and economic dimensions. In addition, the significant effect of (1) labor and (2) plant production amount in economic and environmental performance highlighted the necessity of educating aquaponic operators with the required skills and experiences to optimally operate the aquaponic system, and to maximize systems plant co-production using skillful labor.

5.4. Discussion

5.4.1. Space Heating Improvement:

Energy demand for space heating is considered to be directly proportional to the Heating Degree Days (HDD) for any specific location and time period (J. Chen, 2019; Jiang, Li, Wei, Hu, & Li, 2009). Considering a control level of 23 °C, based on the greenhouse building that the aquaponic system was located in, HDDs are illustrated in Figure 24 for the investigated aquaponic system (all three year-round cycles) as well as other worldwide locations.

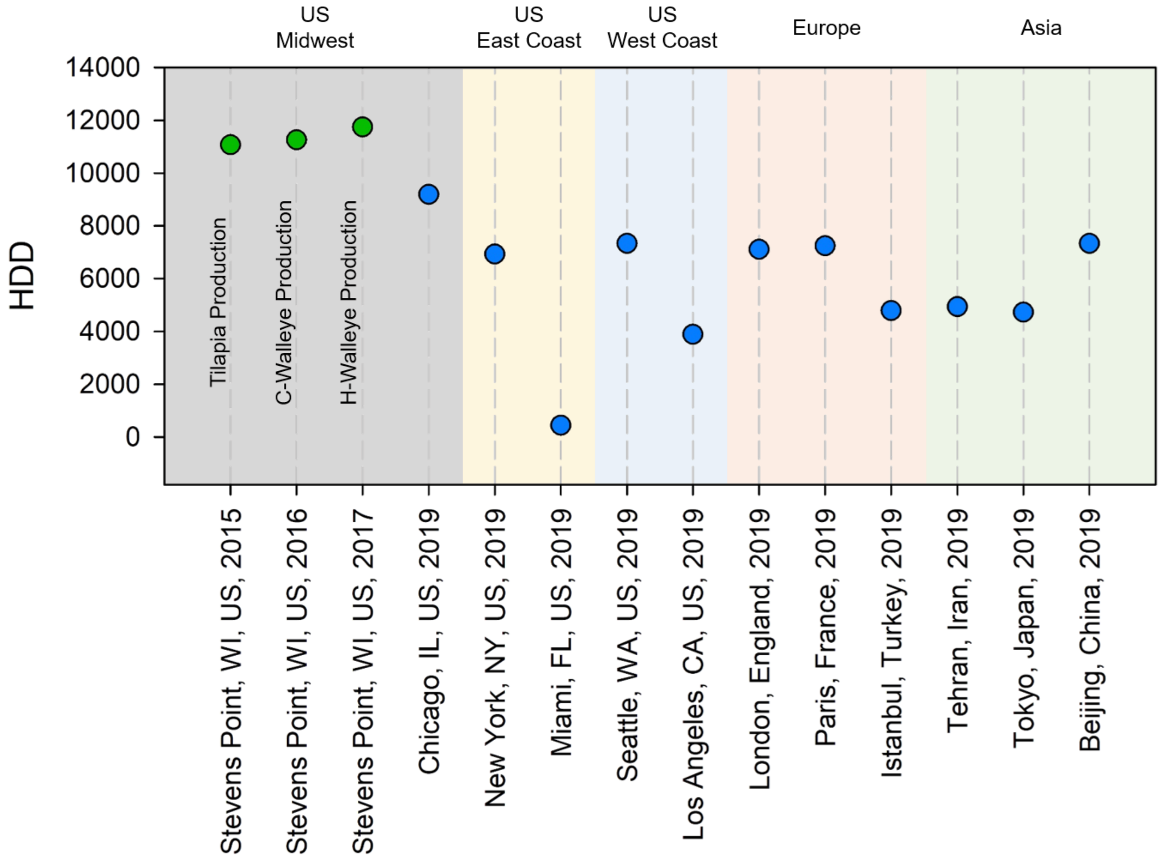

Figure 24. Heating Degree Days (HDDs) for the investigated aquaponic three year-round cycles as well as other locations (weatherdatadepot, 2020).

As shown in Figure 6, due to relatively higher HDDs for the investigated aquaponic system compared to warmer locations, the overall space heating requirements are also expected to be comparably higher. Thus, optimizing the total amount of heating requirements could be beneficial by tangibly reducing the overall environmental impacts as well as the total associated heating costs in cold weather climates. Strategies to improve indoor space heating efficiency should be adopted (Bohnes et al., 2018; Ghamkhar, Hartleb, et al., 2020). These strategies include: (a) Lowering the heat loss by selecting glazing materials with relatively lower heat transfer (e.g. double plastic film, inflated), (b) Insulating north wall in northern hemisphere locations (south wall in southern hemisphere), (c) Insulating the lower portion of side walls (e.g. polystyrene insulation), (d) Installing perimeter insulating barrier, (e) Using night curtains to limit night-time heat loss, and (f) Reducing air leaks and infiltration (e.g. wind breaks) (Pade & Nelson, 2005). It is important to mention that the reduction of heating costs is expected to outweigh the higher initial investment costs for the aforementioned strategies to assure economic favorability.

5.4.2. Infrastructure Improvement

Results of this study highlighted the important role of system infrastructure in the environmental performance, and its major role in the economic performance of the aquaponic system. To mitigate the environmental impacts and costs of aquaponic system's infrastructure and equipment per production unit, it is crucial to increase infrastructure's effective lifespan by proper management and operation. Strategies to achieve longer system lifetime include (1) The selection of suitable tank material and size, and (2) Adequate water circulation and aeration.

Despite the compatibility of varying fish tanks to be used in aquaponics, plastic or fiberglass round tanks with flat (or conical) bottoms are preferred, as they have a relatively high lifetime and also facilitate the cleaning process. Regular cleaning of the fish tanks (to get rid of excess food and excrete) will help to extend the systems operation horizon by maintaining infrastructure's quality. In addition, to prevent excessive waste generation, it is important to prevent over-stocking by the choice of appropriate tank size (based on recommended stocking density for different species). Furthermore, effective water circulation and aeration to maintain the aerobic environment is crucial to prevent excessive waste generation through anaerobic organisms and algae growth that can clog to system equipment.

5.4.3. Scale-Up Implications

A larger-scale operation of aquaponic systems results in an increase in both costs (initial, operational, maintenance, etc.) and revenues (production quantity). However, assuming that the scale-up would manipulate similar technologies but different element sizes (cost-to-capacity method) (Baumann, 2018), the increase in revenues is anticipated to outweigh the increase in costs at higher scales (costs would increase in a lower rate) (Asciuto, Schimmenti, Cottone, & Borsellino, 2019; Rakocy, Bailey, Shultz, & Danaher, 2011; Wu et al., 2019). To evaluate the revenue-cost trade-offs for aquaponic system scale-up, six data points from other studies with a similar environmental setting (located in US-Midwest) have been identified and compiled with three data points from this study (Rupasinghe & Kennedy, 2010; Xie & Rosentrater, 2015). The trend lines for system costs and revenue based on varying production capacities (quantified by kg fish per annum) are drawn out (Figure 25). Cash flow modeling based on a polynomial (for costs) and linear (for revenues) trend lines resulted in an acceptable regression ($R^2 > 0.99$).

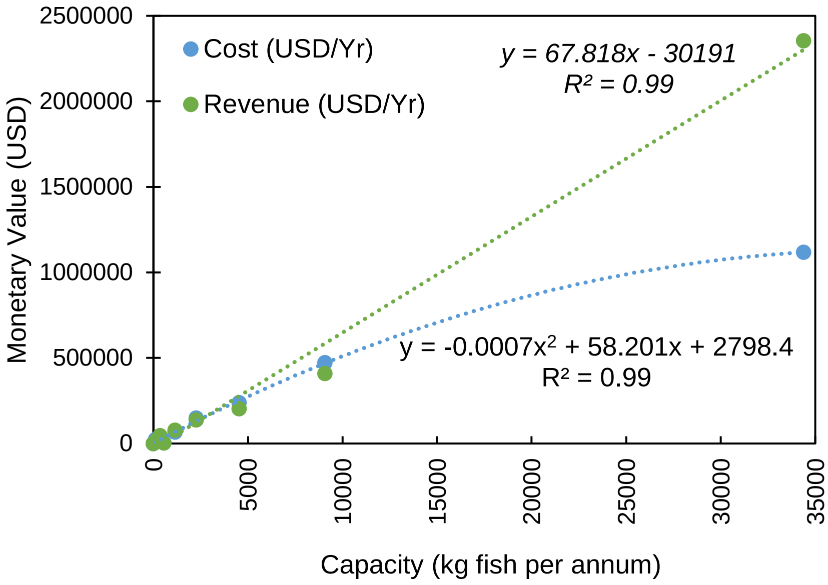

Figure 25. Aquaponic systems annualized cost and revenue based on fish production per annum. Data include 3 data points from this study, three data points from Xie and Rosentrater (2015) (levels: lab, pilot, farm), and three data points from Quagrainie et al. (2018)(levels: small, medium, and large farm). Annualized costs are calculated as Equivalent Annual Cost (EAC). System lifetimes are 20 years (this study), 10 years (Quagrainie et al. (2018)), and 7.53 years (Xie and Rosentrater (2015)).

Despite the variations regarding the inventory parameters and system boundaries in the investigated studies, the analysis indicates an elevated profitability margin (net revenues - net costs) by the increase in system's production capacity. In addition, the projected profitability margin suggests a minimum production capacity of ~3.2-ton fish per annum to assure a net positive profitability. To overcome the limitations of this analysis, future studies could focus on the scale-up implications of aquaponic systems using (a) A comprehensive and fixed system boundary and (b) Comparable inventory parameters, to provide a better estimation.

5.4.4. Social Benefits

The benefits of aquaponic food production systems are not limited to the economic (Bich et al., 2020; Greenfeld et al., 2019) and environmental (Bohnes et al., 2018; Ghamkhar, Hartleb, et al., 2020; Jaeger et al., 2019) dimensions. The social outcomes of local aquaponic food production could be profound, following the concepts of industrial ecology in food production (Kendall & Spang, 2020; Niutanen & Korhonen, 2003). The protection of communities' natural ecosystems by producing local favorable food species without resource overuse (Wu et al., 2019), and providing sustainable food production alternatives with potential domestic market benefits (Greenfeld et al., 2019) are two major social benefits associated with aquaponic implementation. Future research could be centered on evaluating the benefits of aquaponics by accounting net social, environmental, and economic benefits. Moreover, case specific challenges on the industrial-level aquaponic operation, considering different set up factors (e.g. warm-weather vs. cold-weather) could be further investigated.

5.5. Conclusion

An integrated environmental and economic evaluation of a cold-weather located aquaponic system, considering three operational year-round cycles (tilapia, conventional walleye, and hybrid walleye) was presented in this paper (using LCA and EA). As material and energy inputs and outputs were changing among different years (to adjust the system requirements based on varying environmental and production conditions), the environmental impacts as well as economic implications were consequently different. The major finding of this study can be excerpted as: (a) Heat, electricity, aquafeed, and infrastructure were the major contributors of the environmental impacts; (b) Co-production of plants from the aquaponic system was essential to elevate environmental and economic performance. (c) Infrastructure, labor and heat (in terms of costs) were the major economic contributors of the aquaponic system; (d) Leveraging both environmental and economic evaluations, results suggest that heat and infrastructure were the two key parameters that should be prioritized for optimal usage in the investigated aquaponic system. Practical approaches to achieve this are (1) Applying effective space heating strategies, and (2) Extending system’s lifespan through adequate operation and management.

5.6. Acknowledgement

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6. Chapter 6: Sustainable Aquafeeds – using aquafarmer preference to inform a multi-criteria decision analysis

This chapter was adapted from: Ghamkhar, R., & Hicks, A. (2021). Sustainable Aquafeeds: Using Aquafarmer Preference to Inform a Multi-criteria Decision Analysis. ACS Agricultural Science & Technology.

Comparative environmental impact assessment of current and promising aquafeeds has been investigated in Chapter 3. To evaluate how these aquafeeds perform, considering all aspects of decision making in addition to environmental impacts, a multi-criteria decision analysis is performed here.

<u>Authorship contribution statement</u>

Ramin Ghamkhar: Designed Research, Performed Research, Analyzed Data, Wrote the Paper.

Andrea L. Hicks: Designed Research, Provided Feedback, Wrote the Paper.

6.1. Introduction

It is anticipated that the global fish consumption will rise from 111,697 million tons in 2006 to 151,771 million tons by 2030 (Msangi et al., 2013). This consumption increase is mainly triggered from two root causes; the prospective global population increase, and the change in humans' dietary habits (Ghamkhar & Hicks, 2020). Due to the limited capacity of commercial fishing through capture fisheries, aquaculture is an attractive food production technology to meet the growing demand for aquatic species (Rigby, Davis, Bavington, & Baird, 2017). Aquaculture is the practice of farming aquatic organisms (fish and seafood) by intervened rearing processes (e.g. stocking, feeding, protection from predators, etc.) to enhance production (FAO, 2018). Strategies for sustainable industrial aquaculture need to be considered, analyzed, and implemented to address the prospective need (Goddek & Körner, 2019; Wu et al., 2019).

Aquafeed is one of the main drivers of material and energy flows in the aquaculture systems; ascribing it a significant role regarding environmental, economical, and technical aspects in aquaculture food production (Basto-Silva et al., 2019; Ghamkhar, Boxman, et al., 2020; Ghamkhar & Hicks, 2020). Aquafeeds' contribution to the overall environmental impacts, economic performance, and production quality of the aquaculture systems is distinctly highlighted and investigated in many recent studies (P. Chen, Zhu, Kim, Brown, & Huang, 2020; Y. Chen, Wang, & Xu, 2020; Ghamkhar, Hartleb, et al., 2020; Lobillo-Eguíbar, Fernández-Cabanás, Bermejo, & Pérez-Urrestarazu, 2020; Maiolo et al., 2020; Nalawade & Bhilave, 2011; Xie & Rosentrater, 2015). Forage-sourced fish meal and fish oil are the traditional main providers of essential nutrients in formulated aquafeeds, making them the major material and energy inflows in aquafeed production (Naylor et al., 2000). To prevent single-source dependency on a finite resource, there is a growing desire to implement alternative ingredients (to fish meal and fish oil) in aquafeeds formulation to obtain acceptable production while mitigating the ecological burdens (Marvin et al., 2020; Naylor et al., 2009; Nathan Pelletier et al., 2018). It is necessary to quantify the environmental tradeoffs which may occur due to the usage of non-conventional aquafeed ingredients.

With respect to the environmental implications, Ghamkhar and Hicks (2020) investigated the comparative environmental impacts of various fed aquafeed formulations, including fish oil and meal free diets, in a midpoint life cycle assessment (LCA) using a holistic set of 12 relevant indicators (TRACI, Biotic Resource Use, and Water Intake). The study suggests that replacement alternatives that incorporate (1) energy-efficient substitutions for fish oil (e.g. plant-based canola oil) and (2) less material-intensive substitutions for fish meal (e.g. poultry byproduct, soybean meal) are promising strategies to mitigate the overall ecological damages derived from aquafeeds. With respect to the economic implications, Arikan and Aral (2019) have performed a comprehensive technical and economic analysis of seabream and seabass production, using small-scale, medium-scale, and large-scale aquaculture systems (n=65). Their findings indicate that aquafeed contributes to >60% of total costs (variable and fixed) in all investigated systems.

Strategies to lower the share of aquafeed cost (e.g. domestic fish meal production) need to be explored (Hardy, 2010). With respect to the production performance, Adelizi et al. (1998) analyzed the production of trout (growth and tissue analyses) utilizing nine formulated diets with varying protein (~37%-51%) and fat inclusion (~10%-18%). The results suggest that the diet with the highest digestible protein content (fishmeal-based, soybean free) outperforms other diets in terms of fish weight gain, protein intake efficiency, and fillet flavor. John Davidson et al. (2016) compared the production of post-smolt Atlantic salmon using different formulated aquafeeds (fishmeal-based vs. fishmeal-free) with similar protein and crude fat inclusion (42% and 27% consecutively), and found that the growth, survival, and feed conversion ratios (FCRs) were unaffected by diets' fishmeal inclusion, when protein and fat levels are kept similar.

Considering the implications of aquafeeds in varying relevant dimensions (environmental, economic, and technical), the selection of the most sustainable aquafeed is a challenge for decision makers and seafood producers. To accomplish that, it is necessary to consolidate many factors (e.g. the overall cost of aquafeed, its impact on final fish product, its impact on water quality, etc.). These factors are usually conflicting, and if the decision makers want to incorporate all the influencing dimensions, they may face the dilemma of which option to select based on the available commercial choices (Luna, Llorente, & Cobo, 2019).

Multi-Criteria Decision Analysis (MCDA), which is an integrated sustainability evaluation methodology, can be used as a platform to compare the relative sustainability of aquafeeds with respect to the pertinent features and characteristics (Burek & Nutter, 2019; J.-J. Wang, Jing, Zhang, & Zhao, 2009). In MCDA, a multi-dimensional decision making approach is undertaken to tackle complex problems, entailing varying forms of data, antagonistic objectives, and multiple interests and perspectives (Bartzas & Komnitsas, 2020; Vergara-Solana, Araneda, & Ponce-Díaz, 2019; J.-J. Wang et al., 2009). For example, Yin, Takeshige, Miyake, and Kimura (2018) have performed a MCDA to identify the most suitable coastal aquaculture sites in Menai Strait (UK), incorporating environmental and socio-economic factors. Considering the wide variety of potential functions for the investigated coastal areas (e.g. transportation, recreation, leisure fishing, etc.), this study has considered stress minimization on ecosystems, productive harvest improvement, and conflict mitigation among coastal water users to select the most suitable locations. Safarian, Sattari, Unnthorsson, and Hamidzadeh (2019) conducted a MCDA among bioethanol production systems (i.e. agricultural vs. agricultural waste biomass) in Iran, using seven relevant economic, energy, and environmental factors. Their results indicate that despite most agricultural systems, agricultural waste systems (e.g. sugarcane) are suitable feedstock for bioethanol production in Iran, since they are cost-effective, renewable, and abundant.

This work seeks to implement MCDA to evaluate the sustainability of varying formulated aquafeeds (e.g. fish meal and oil free diets) based on their relevant economic, environmental, commercial, and technical characteristics. To accomplish that, the following three steps are performed: first, a survey is developed and distributed among the licensed commercial aquafarmers in the State of Wisconsin (US) to obtain real-world characteristics scores (weightings). Second, a holistic set of formulated aquafeeds (twelve) with varying ingredients inclusion (e.g. fish meal and fish oil) have been obtained from the authors' previous work (Ghamkhar & Hicks, 2020). These aqua-diets span a wide domain of ingredients inclusion and consequent biological and nutritional characteristics. Thus, they will provide an acceptable range of prospective feeding formulations that can be successfully used for aquafarming. Third, MCDA is performed based on the elicited rankings and aquafeed options. A MCDA hierarchy for this research is illustrated in Figure 26. Four hypothetical scenarios (aquafarmers with prime considerations of: environmental impact mitigation, final product maximization, cost minimization, and fish meal substitution) have also been further evaluated and discussed.

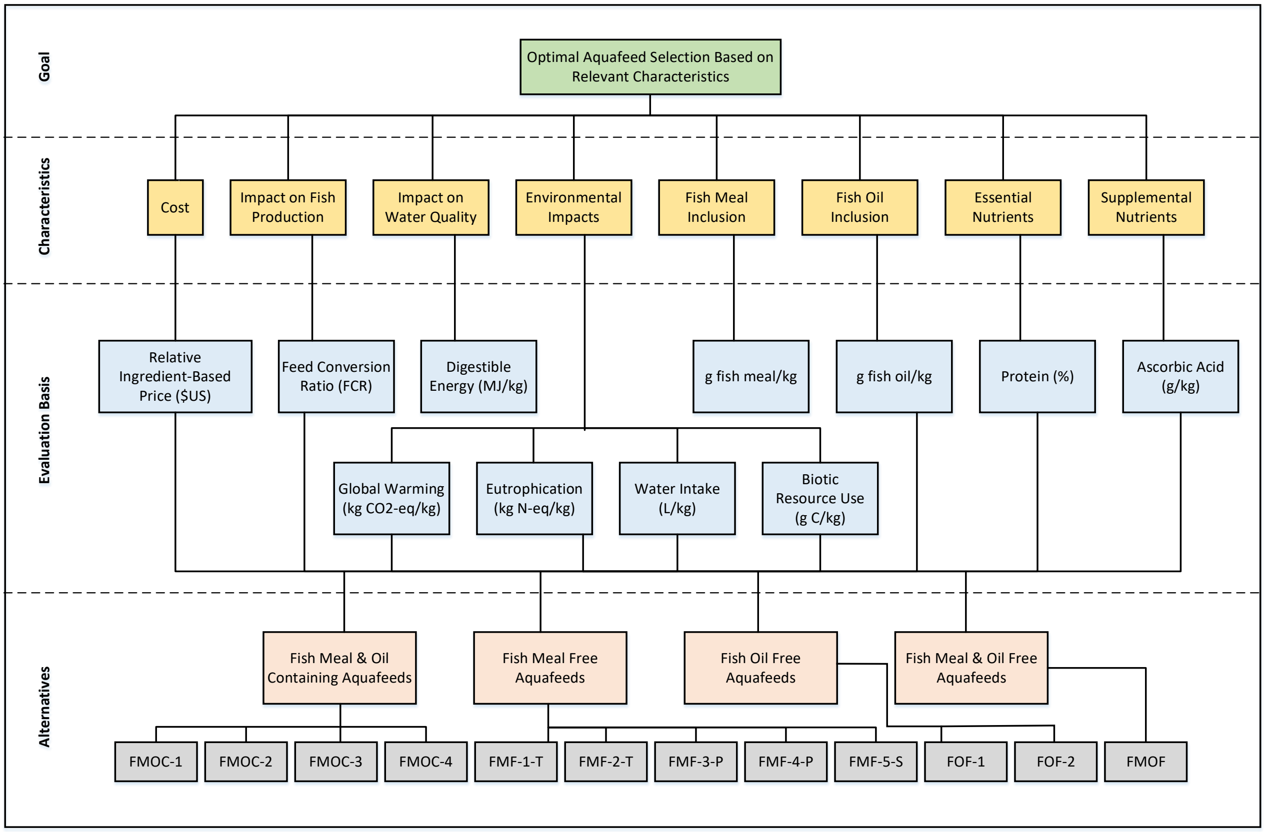


Figure 26. Multi-Criteria Decision Hierarchy for aquafeed selection. FMOC-1, FMOC-2, FMOC-3, and FMOC-4 refer to Fish Meal and Oil Containing Diets. FMF-1-T and FMF-2-T refer to Fish Meal Free (but fish oil containing) diets with Terrestrial replacements (poultry by-product and blood meal respectively). FMF-3-P and FMF-4-P refer to Fish Meal Free (but fish oil containing) diets with plant-based replacements (peanut meal and soybean meal respectively). FMF-5-S refers to Fish Meal Free diet with seafood by-product replacement. FOF-1 and FOF-2 refer to Fish Oil Free (but fish meal containing) diets with vegetable (canola) and vegetable and protist-based replacements (respectively). Finally, FMOF refers to Fish Meal and Oil Free Diet with terrestrial, seafood by-product, and plant-based replacements.

6.2. Materials and Methods

MCDA is defined as "an operational evaluation and decision support approach that is suitable for addressing complex problems featuring high uncertainty, conflicting objectives, different forms of data and information, multi-interests and perspectives, and the accounting for complex and evolving biophysical and socio-economic systems” (Khan, 2019; J.-J. Wang et al., 2009). To develop a MCDA, the following steps are required: the collection of the existing (or potential) options to select as a decision (section 5.2.1), the elicitation of decision characteristics, including their relative importance (sections 5.2.2, 5.2.3), the assignment of comparative values to the characteristics (section 5.2.4; subsections 5.2.4.1 to 5.2.4.5), and the selection of the proper analysis methodology (section 5.2.5). The following sections will elaborate on the aforementioned steps undertaken in this work, as well as the methodological approaches for Graphical Analysis for Interactive Assistance (GAIA, section 5.6) and hypothetical scenario analysis (section 5.2.7).

6.2.1. Existing and Potential Options (Decisions)

Twelve different aquafeeds that have been successfully formulated and experimentally utilized to produce seafood (to ensure practicality of diets usage) were extracted from previous work by the authors (Ghamkhar & Hicks, 2020). Four fish meal and oil containing diets with, referred as FMOC-1, FMOC-2, FMOC-3, and FMOC-4, with varying ingredients and protein contents were considered (Akiyama, 1990; Carter et al., 2003; John Davidson et al., 2016). Two fish meal free diets (FMFs), in which fish meal is replaced with terrestrial poultry by-product and terrestrial blood meal were selected, which are referred as FMF-1-T and FMF-2-T respectively (El-Sayed, 1998; Rossi Jr & Davis, 2012). Two fish meal free diets, in which fish meal is replaced with plant-based peanut meal and soybean meal were opted, which are referred as FMF-3-P and FMF-4-P respectively (Adelizi et al., 1998). A forage fish meal free diet, in which fish meal is replaced with fish processing industry by-products, were considered and referred as FMF-5-S (Ian Forster et al., 2004). FOF-1 and FOF-2 refer to the fish oil free (FOF) diets, in which fish oil is replaced with vegetable-based (canola) oil, and both vegetable-based (canola) and single-cell protist-based (Thraustochytrid) oils (Byreddy, 2015; Carter et al., 2003). Finally, a fish meal and fish oil free diet, referred as FMOF, in which full replacement of fish meal and oil with terrestrial meal (poultry by-product), plant-based meal (mixed nuts), and seafood by-product (whitefish trimming) ingredients is selected (John Davidson et al., 2016). Specifications regarding the ingredients materials and amounts are provided in details in the supporting information (SI) file (Tables S1 to S12). Further detailing specifications regarding corresponding life cycle impacts database, assumptions, and comments can be found in another paper by the authors (Ghamkhar & Hicks, 2020).

6.2.2. Decision Characteristics Elicitation

In order to evaluate the impact of input data on the MCDA model output, two approaches was undertaken:

(1) A survey was developed and distributed among 40 aquafarmers, detected from the Wisconsin Department of Agriculture, Trade, and Consumer Protection’s list of fish farms as commercial

licensed aquafarms (school farms excluded) (DATCP, 2020). Farmers are producing a range of aquatic species (e.g. tilapia, trout, salmon, and perch). Eight surveys have been received back fulfilled with an acknowledgement on performing research based on the provided data. It is important to highlight that the number of respondents depends on the survey goals. A 20% response rate for the purpose of this survey is a reasonable outcome, as it meets the purpose of incorporating producers' realistic scores within the analysis, which often lacks in previous MCDA studies. We should also note that many fish farms are teetering on the brink of closure right now due to the Covid pandemic(Chris Hartleb, 2020; Hicks et al., 2020), which means that there may be even fewer farms in Wisconsin than are listed on the permit registry. Despite the aforementioned limitations, structure of the analysis based on realistic scenarios is valuable for the purpose of this analysis because (a) incorporation of aquafarmers scores for decision characteristics (either harmonious or discordant) provides the opportunity to analyze outcomes based on potential variations affecting the producers' practice, and (b) the majority of MCDA studies have been performed solely around hypothetical decision scores, in which potential real-case variations may exist.

(2) Besides the criteria weightings obtained from the aquafarmers, four additional scenarios were defined and evaluated, as the typical approach undertaken for MCDA, representing hypothetical scenarios for prioritizing (a) environmental considerations, (b) initial costs minimization, (c) final product maximization, and (d) fish meal replacement (further described in section 2.7).

In general, it is easier for the decision makers to rank their preferences rather than give weightings to them. Therefore, the survey has been developed in such a way to attribute ranking scores to different characteristics by the decision makers (i.e. aquafarmers). A copy of the survey instrument is provided in the SI (Table S13).

6.2.3. Weightings

To attribute appropriate weightings to different characteristics that influence producers' decisions on the selection of aquafeeds, eight farmers ranked the relevant characteristics based on their level of importance (survey). The characteristics are 'cost', 'impact on fish production', 'impact on water quality', 'impact on the environment', 'use of fish meal', 'use of fish oil', 'inclusion of essential nutrients', and 'inclusion of supplemental nutrients'. The elicited rankings have been converted to weightings using Rank-Order Centroid (ROC) method, which is known as one of the best performing rank-to-weighting conversion methods due to non-linear function of weights (Sureeyatanapas, 2016). Weightings to different ranked characteristics based on ROC can be attributed using the following algorithm:

$$W_i = \frac{1}{M}\sum_{n=i}^{M}\frac{1}{n} \qquad \text{Eq. [1]}$$

In which W_i is the attributed weighting to the characteristic ranked i, and M is the total number of characteristics (items). A summary of the survey results regarding the attributed rankings to different characteristics (by decision makers) as well as the associated calculated ROC weightings are provided in the Appendix (Table D14).

6.2.4. Value Assignments to Characteristics

6.2.4.1. Cost

Assuming similar pellet production and product processing (e.g. grinding, extruding, drying, etc.) for the investigated aquafeeds (Ghamkhar & Hicks, 2020), the comparative prices for different aquafeeds can be directly correlated to the quantities and types of ingredient components. Comparative ingredient-based prices have been elicited based on the component inclusion of varying ingredients for each diet (Arru, Furesi, Gasco, Madau, & Pulina, 2019; Rana, Siriwardena, & Hasan, 2009). Results are presented in Figure 27a.

The United Nations' Food and Agricultural Organization (FAO) dataset for monitoring and analysis of food prices is used to attribute the most accurate ingredient prices for different aquafeeds (most recent annual average international export prices from 4/2019 to 4/2020). For the ingredients which did not exist in the database, an online web search was used to elicit the best estimation for the merchandised price per gram of ingredient based on available products. Attributed price values based on each aquafeed's ingredient are provided in the Appendix (Table D15).

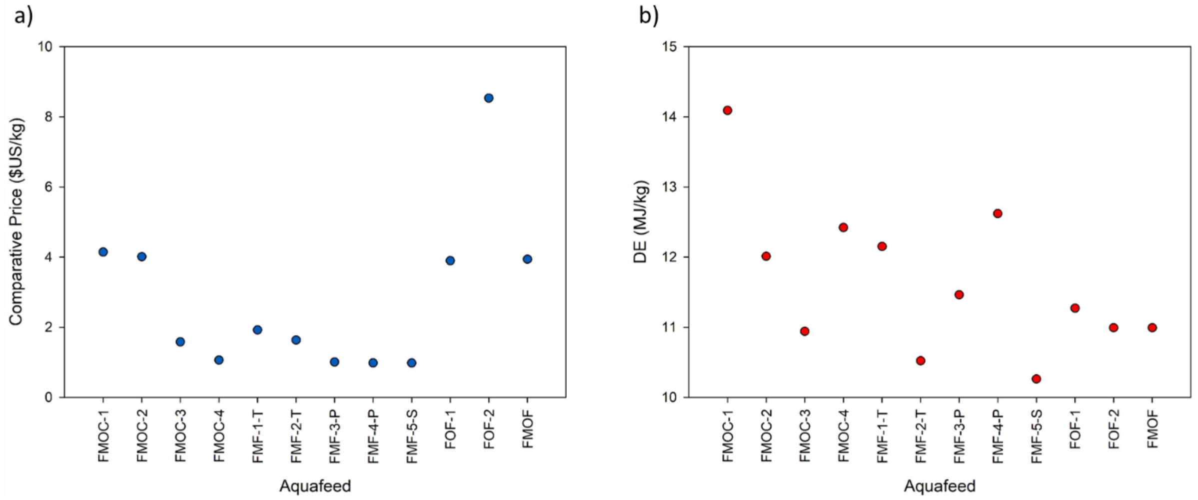


Figure 27. a) Aquafeeds comparative cost estimation: relative costs for the investigated aquafeeds based on the ingredient components. b) Aquafeeds impact on water quality estimation: Digestible Energy (DE, MJ/ kg) values for the investigated aquafeeds.

6.2.4.2. Impact on Fish Production

To evaluate the impact of using different aquafeeds on the quantity of produced fish (gained live-weight product), feed conversion ratio (FCR) is used as the common quantification approach to characterize the efficiency of nutrients intake by species (Ghamkhar & Hicks, 2020; Philis et al., 2019). FCR is defined as the amount of consumed dry weight aquafeed per unit of gained live-weight product. A lower FCR for an aquafeed indicated higher gain of ultimate product (e.g. fish) using the investigated aquafeed. The attributed FCRs for the investigated aquafeeds are tabulated in the Appendix (Table D16).

6.2.4.3. Impact on Water Quality

The dietary-origin waste is reported as the major contributor to the final waste in aquaculture systems (Bélanger-Lamonde et al., 2018; C. Y. Cho & Bureau, 1997). The undigested portion of ingested feed (= ingested portion – digested portion) can be attributed to the reduction of water quality (Aksnes & Opstvedt, 1998; C. Y. Cho & Bureau, 1997). In an effort to quantify the comparative digestibility of the investigated aquafeeds, the values for digestible energy (DE, MJ/kg) have been elicited with respect to different ingredients for rainbow trout (C. Cho, Slinger, & Bayley, 1982). Results are shown in Figure 27b (Table D17 of the Appendix). Higher overall DE for an aquafeed indicates less undigested feeding portion and waste, and consequently, higher rearing water quality.

6.2.4.4. Impact on the Environment

Life Cycle Assessment (LCA) is a methodology to quantify and assess the environmental impacts of products or processes over their entire or partial life cycle (based on the defined system boundaries). A standardized LCA follows the four steps defined by the International Standard Organization (ISO14040) (ISO-Norm, 2006; Temizel-Sekeryan et al., 2020): (1) Goal and scope definition, in which the system's boundary and evaluation methods are defined; (2) Life-cycle inventory, in which all the material and energy flows (inflows and outflows) to the system are quantified (Temizel-Sekeryan & Hicks, 2020); (3) Life-cycle impact assessment, in which the quantified environmental impacts are calculated and evaluated; and (4) Interpretation, in which conclusions and recommendations are made. For this study, the quantified environmental impacts of different aquafeeds are elicited from a previous LCA, in which the US EPA's TRACI 2.1 is used as the midpoint impact characterization tool, along with the stand alone categories of biotic resource use and water intake (Bare et al., 2012; Ghamkhar & Hicks, 2020). The main impact categories that have been considered for this study are global warming (GW), eutrophication (EU), biotic resource use (BRU), and water intake (WI). The selected impact categories are recognized as the most relevant categories in terms of resource extraction (biotic and water resources) and emissions (eutrophication and global warming potential) with respect to aquafeeds (Ghamkhar & Hicks, 2020; Luna et al., 2019). Quantified impacts are provided in Figure 28, as well as Table D19 of the Appendix.

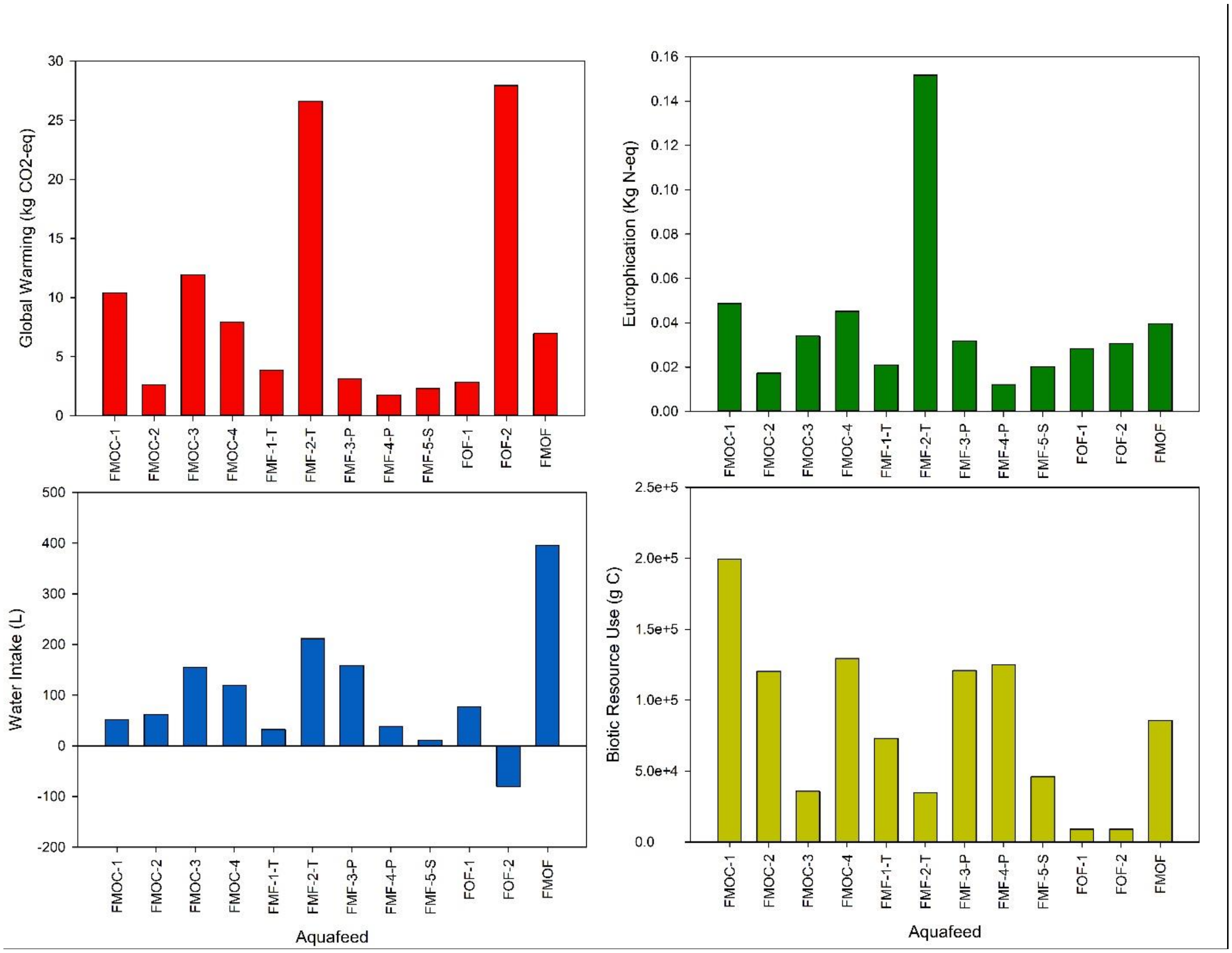


Figure 28. Quantified Environmental Impacts of aquafeeds based on unit mass (1 kilogram) of protein provision.

In order to provide a comparative score for this criteria, the environmental impacts in each of the impact categories are first normalized (attributing 1 to the highest) and then considered as equally important with respect to other impact categories (i.e. the overall weighting for environmental impacts is equally distributed among all indicators).

6.2.4.5. Inclusion of Essential and Supplemental Nutrients

To quantify the incorporation of essential nutrients in the aquafeeds (rather than the use of supplements to make up deficits), protein inclusion (in terms of crude protein percentage) is selected as the major consideration in aqua-diets formulations (N. R. Council, 2011; De Silva & Anderson, 1994; Ghamkhar & Hicks, 2020). To specify the incorporation of supplemental (sub-essential) nutrients in the aquafeeds, supplemental Vitamin C (ascorbic acid, Stay C) has been selected as the necessary nutrient that is required to be supplied to aquatic animals to acquire optimal growth and health (Dabrowski, 2000; Essays, 2018). The attributed protein Inclusions (in %) and supplemental vitamin C (in g/kg) for the investigated aquafeeds are tabulated in the Appendix (Table D16).

6.2.5. Analysis Methodology (Multiple Criteria Decision)

The Preference Ranking Organization method for Enrichment Evaluation (PROMETHEE II) has been selected as a standard and widely used method for multi-criteria decision analysis (Brans & Vincke, 1985; De Smet & Lidouh, 2012; Sari, Kandemir, Ceylan, & Gül, 2020). PROMETHEE II is performed using the following procedure (Vukelic et al., 2017):

The first step is to provide comparative, unit-less and harmonized values among varying criteria (evaluation matrix normalization). Equation 2 is used for normalizing direct (where maximizing is desired), and equation 3 is used for indirect (where minimizing is desired) criteria.

$$R_{ij} = \frac{[X_{ij} - \min(X_{ij})]}{[max(X_{ij}) - min(X_{ij})]} \quad (i=1,2,\ldots,m;\ j=1,2,\ldots,n) \qquad \text{Eq. [2]}$$

$$R_{ij} = \frac{[\max(X_{ij}) - X_{ij}]}{[max(X_{ij}) - min(X_{ij})]} \quad (i=1,2,\ldots,m;\ j=1,2,\ldots,n) \qquad \text{Eq. [3]}$$

In which X_{ij} is the performance measure of i^{th} alternative with respect to j^{th} criterion (characteristic).

The second step is calculation of pairwise evaluative differences. In this step, the difference of each alternative with respect to other alternatives is calculated.

The third step is the calculation of the preference function. The difference between the evaluations obtained in the second step is translated into a preference degree, ranging from 0 to 1, using the following formula (equations 4 and 5) (Brans & Mareschal, 1994; Sari et al., 2020).

$$Pj\ (i, i') = 0;\ if\ Rij \leq Ri'j \qquad \text{Eq. [4]}$$

$$Pj\ (i, i') = Rij - Ri'j;\ if\ Rij > Ri'j \qquad \text{Eq. [5]}$$

In which R_{ij} and $R_{i'j}$ are the normalized values for two selected alternatives (i^{th} and i'^{th}) with respect to j^{th} criterion (characteristic).

The fourth step in the calculation of aggregated preference. In this step, the criteria weights are taken into account using the following formula (equation 6) (Athawale & Chakraborty, 2010).

$$\pi(i, i') = \frac{\Sigma_{j=1}^{m}(W_j P_j(i, i')}{\Sigma_{j=1}^{m} W_j} \qquad \text{Eq. [6]}$$

In which W_j is the attributed weight to the j^{th} criterion (characteristic), and $P_j(i,i')$ is the preference function of the two selected alternatives (i^{th} and i'^{th}) with respect to j^{th} criterion.

The fifth step is determination of the leaving and entering flows. In this step, the extent of which an alternative dominates the other alternatives (leaving flow, equation 7), or an alternative is dominated by other alternatives (entering flow, equation 8) is expressed using the following formulas (equations 7 and 8).

$$\varphi^{+}(i) = \frac{1}{n-1} \sum_{i'=1}^{n} \pi(i, i') \quad (i \neq i') \qquad \text{Eq. [7]}$$

$$\varphi^{-}(i) = \frac{1}{n-1} \sum_{i'=1}^{n} \pi(i', i) \quad (i \neq i') \qquad \text{Eq. [8]}$$

In which n is the total number of alternatives, and $\pi(i,i')$ is the aggregated preference of the alternatives i and i'.

The final and sixth step is calculation of the net outranking flows (φ) and ranking determination. In this step, the net outranking flows are calculated using the following formula (equation 9). Then, alternatives are ranked from the most preferred (highest net outranking flow) to the least preferred (lowest net outranking flow).

$$\varphi(i) = \varphi^{+}(i) - \varphi^{-}(i) \qquad \text{Eq. [9]}$$

6.2.6. Graphical Analysis for Interactive Assistance (GAIA)

To perform further analysis regarding MCDA results, a GAIA plane for each real case and hypothetical scenario is plotted using Visual PROMETHEE 1.5 software (Brans & De Smet, 2016). The aim of using GAIA in this MCDA is to provide the most possible information from a 2-D representation (De Smet & Lidouh, 2012). Four main types of information are provided by GAIA plane (Mareschal, 2016): (1) alternatives (actions) are represented by points; alternatives with similar profiles will be closer to each other (and vice versa). (2) characteristics (criteria) are represented by axes; characteristics with similar preferences have axes close to each other (and vice versa). (3) Decision axis (the red axis) which represents all criteria values and weights; the orientation of the decision axis indicates the relative contribution of characteristics to the final outranking. (4) The orthogonal projection of each alternative (action) on each criteria (characteristic) axis will illustrate the performance of each alternative with respect to each characteristic.

6.2.7. Alternative Scenario Analysis

To evaluate the MCDA results in varying scenarios, four hypothetical stakeholder perspectives have been further evaluated. In the first perspective, the stakeholder (decision maker) values the most on mitigating environmental impacts (EIM). Thus, the overall environmental impact criterion weight is equal to all other criteria combined (50:50, weighting ratios for other criteria are equal). In the second perspective, the stakeholder (decision maker) values the most on maximizing fish production (FPM). Then, the overall “impact on fish production” criterion weight is equal to all other criteria combined (50:50, weighting ratios for other criteria are equal). In the third perspective, the stakeholder (decision maker) values the most on minimizing feeding costs (CM). For this reason, the overall “aquafeed cost” criterion weight is equal to all other criteria combined (50:50, weighting ratios for other criteria are equal). In the fourth perspective, the stakeholder (decision maker) values the most on replacement of fish meal with alternative ingredients in the utilized aquafeed (FMR). The aquafeeds (actions) with fish meal as an existing component are eliminated from the analysis and only fish meal free diets are incorporated in the analysis. Furthermore, “use of fish meal” criteria is assigned to the weighting of zero (equal weighting for all other criteria).

6.3. Results

6.3.1. MCDA

A quantitative MCDA, attributed to the different criteria weighting scenarios, is performed based on aquafarmers survey results (presented as farmers A through H). The assigned weightings and consequent MCDA results are shown in Figure 29 with green and blue bar graphs respectively.

In 4/8 scenarios, FOF-1 (the diet in which fish oil is replaced by canola oil) has resulted in the highest net outranking flow. Furthermore, it has ranked among the top four in 7/8 scenarios. Hence, FOF-1 can be stated as the most promising aquafeed based on the real-case scenarios. In addition, FMOC-2 has also performed as the second favorable aquafeed. Despite it not being ranked first in any of the scenarios, it has ranked among the top four in 6/8 scenarios. Thus, FMOC-2 can be stated as the second most favorable aquafeed based on the real case scenarios. Contrarily, FMF-2-T have resulted in the lowest net outranking flow in all investigated (12/12) scenarios. In consequence, compiling all pertinent characteristics and attributed weightings, it can be stated as the least favorable aquafeed to be selected. Compiling all the rankings based on different scenarios, the investigated aquafeeds (actions) can be ranked as: (1) FOF-1, (2) FMOC-2, (3) FMOC-1, (4) FMF-4-P, (5)FMOC-4, (6)FMF-3-P, (7) FMOF, (8) FMF-5-S, (9) FOF-2, (10) FMF-1-T, (11) FMOC-3, (12) FMF-2-T. Overall rankings are assigned based on each aquafeed’s average ranking over all investigated scenarios. Full results regarding the ranking flows for different aquafeeds under different scenarios are provided in table D19 of the Appendix.

Looking at the role of diets formulation in the aquafeeds, results based on the integration of pertinent characteristics indicate that the substitution of fish oil with plant-based canola oil is a promising strategy to achieve a desirable aquafeed (FOF-1). This aquafeed has not only posed relatively acceptable nutrients inclusion and feed conversion ratio, but also mitigated the environmental impacts associated with fish oil production (Ghamkhar & Hicks, 2020). Moreover, the aquafeeds with the supplemental nutrients have mostly resulted in the diet formulations, in which the ultimate production efficiencies (FCR improvement) outperform the relative costs increase (e.g. FMOC-2). Accordingly, the inclusion of supplemental nutrients (Stay C) is another approach to practically elevate aquafeeds favorability. Contrarily, the substitution of fish meal with terrestrial alternatives (e.g. blood meal) has resulted in a significant down-ranking for the corresponding aquafeeds (i.e. FMF-1-T, FMF-2-T). Therefore, the replacement of fish meal with the investigated terrestrial alternatives is not an effective strategy to improve the desirability of aquafeeds.

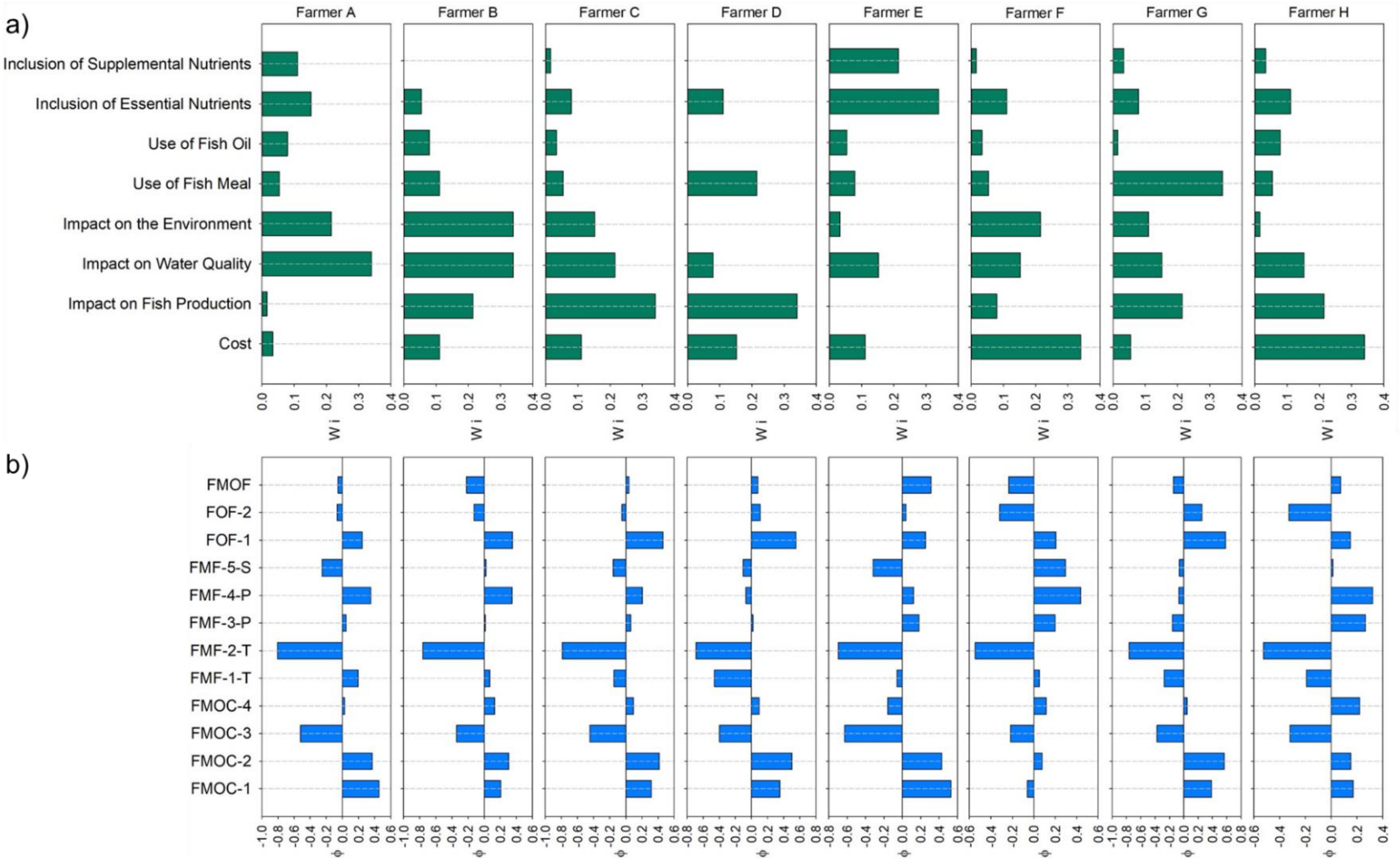
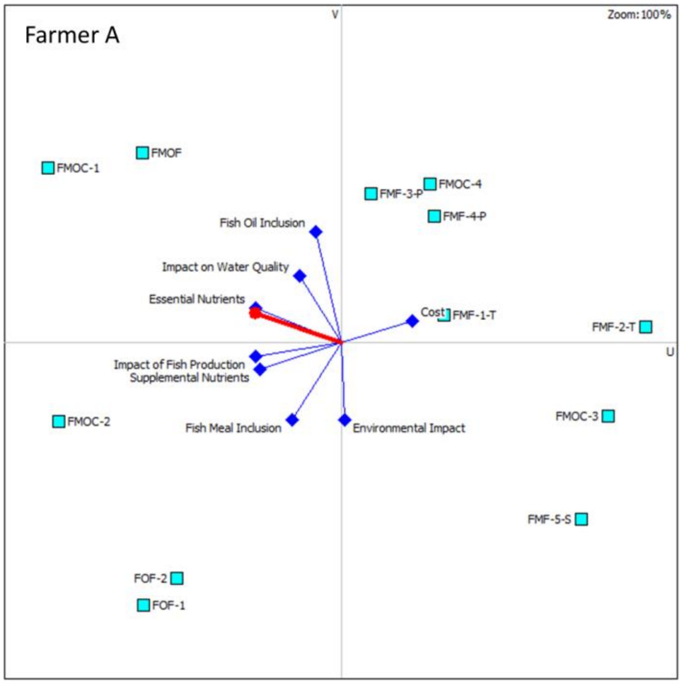


Figure 29. a) Survey-Based weightings (green bars) for the investigated characteristics based on farmers ranking assignment using ROC methodology. b) Net Outranking φ Values for the investigated aquafeeds (blue bars). Aquafeeds with the highest φ values are most preferred and vice versa.

6.3.2. GAIA

To provide the most possible information from a 2-D representation, GAIA plane is developed for all the MCDA scenarios (Figure 30). As mentioned in the methodology section, alternatives (represented by light-blue points) with similar profiles are closer to each other in the GAIA plane. For example FOF-1 and FOF-2 have many similar characteristics (regardless of their relative discrimination; both are fish oil free diets with similar FCRs and Protein inclusion). Consequently, they are located close to each other in most of the GAIA planes. Furthermore, characteristics with similar axis orientation represents how in-line they are with respect to each other. Thus, based on the data and the investigated characteristics, the following statements could be made for most of the scenarios. First, aquafeeds with higher inclusion of essential and supplemental nutrients also exhibit a better impact on fish production (lower FCR). Hence, the most practical way to improve fish production for an aquafarmer is to improve the inclusion of both essential and supplemental nutrients in the utilized diet formulation. Second, cost and environmental impacts are the conflicting characteristics regarding most of the other characteristics. Consequently, if the aquafarmer selects the cheapest aquafeed, or the aquafeed with the least environmental impacts, the selected aquafeed will not perform as desirably in other discriminatory dimensions. Third, the inclusion of fish oil is mostly correlated with an improved impact on water quality. This suggests that the fish oil replacements are highly prone to decrease the quality of rearing water. In addition, the vertical projection of each aquafeed on each characteristic line will demonstrate the relative performance of that aquafeed regarding the selected characteristic. For FOF-1, the positively contributing parameters are fishmeal inclusion, environmental impacts, and the impact on fish production. Consequently, aquafarmers who put high scores for those characteristics (targeting fishmeal-included, environmentally friendly, and efficient aquafeeds) can declare FOF-1 as the best option. For FMOC-2, the positively contributing parameters are impact on fish production, inclusion of supplemental nutrients, and fishmeal inclusion. Consequently, aquafarmers who put high scores for those characteristics (targeting fishmeal and supplemental-included, and efficient aquafeeds) can declare FMOC-2 as the best option. For FMF-2-T, the only characteristics which is relatively favorable for this alternative is cost. As aquafarmers mostly consider other conflicting factors as well when selecting an aquafeed (e.g. quality, ultimate efficiency, etc.), it has never posed a significant overall score.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V
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FMOC-1
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FMF-2-T
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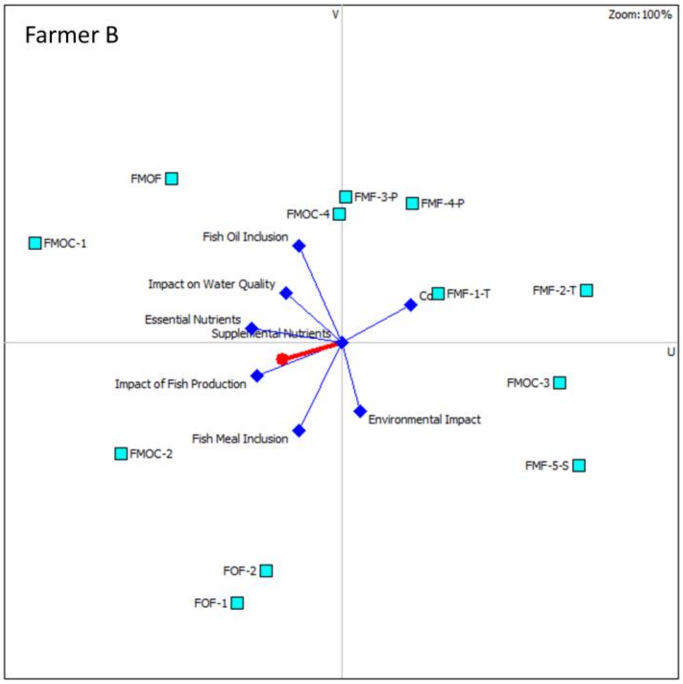
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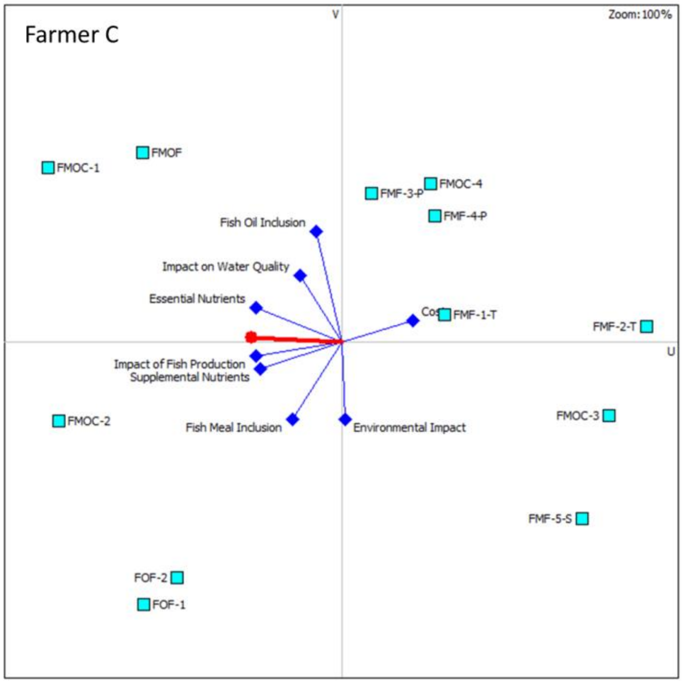
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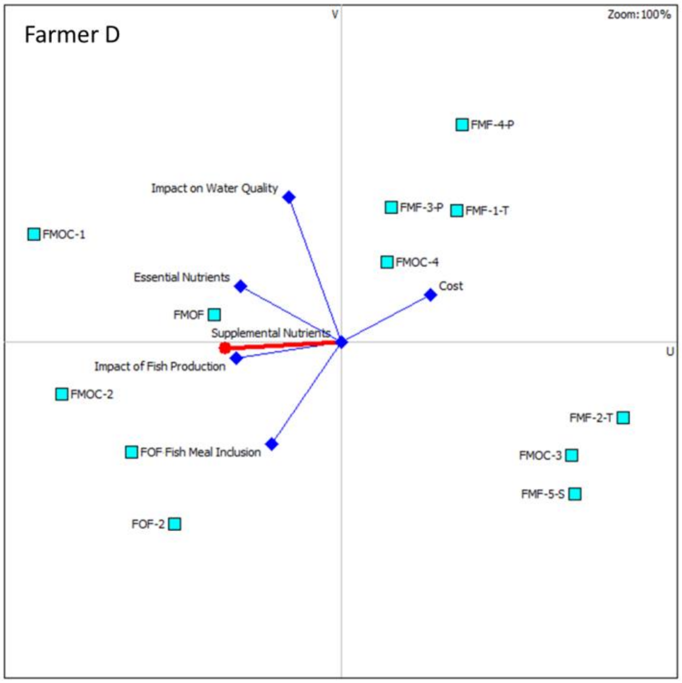
FOF-1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Fish Meal Inclusion
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FOF-2

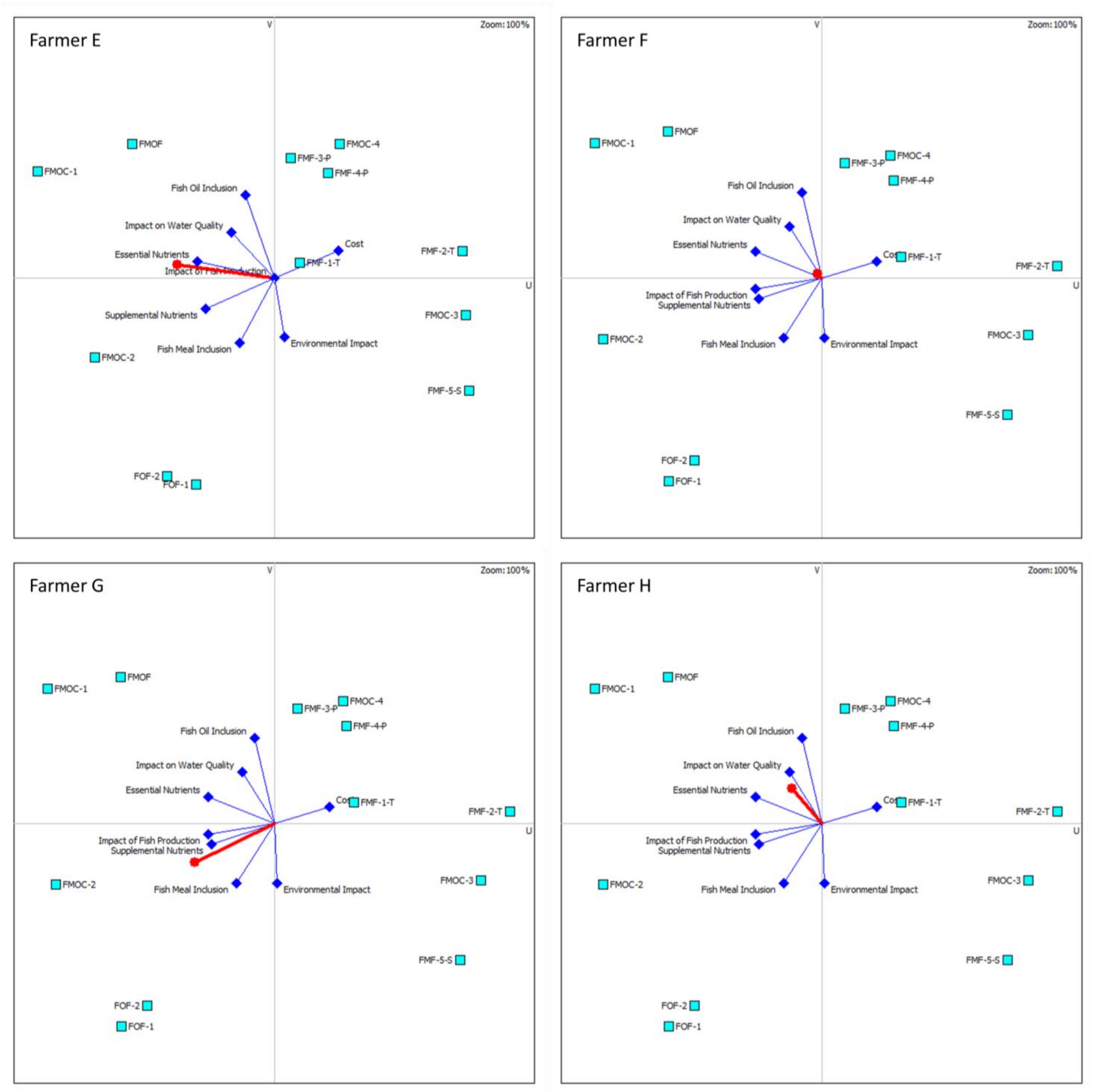

Figure 30. GAIA Planes based on different scenarios.

6.4. Discussion

Four hypothetical aquafarmer perspectives have been further analyzed to evaluate the MCDA results under varying scenarios. These scenarios include stakeholders perspective who outweigh one specific characteristic over the others; and those perspectives are: (1) Environmental Impact Mitigation (EIM), (2) Final Product Maximization (FPM), (3) Cost Minimization (CM), and (4) Fish Meal Replacement (FMR). MCDA is performed under hypothetical scenarios using PROMETHEE II. Results are illustrated in Figure 31 (and Table D20 of the Appendix).

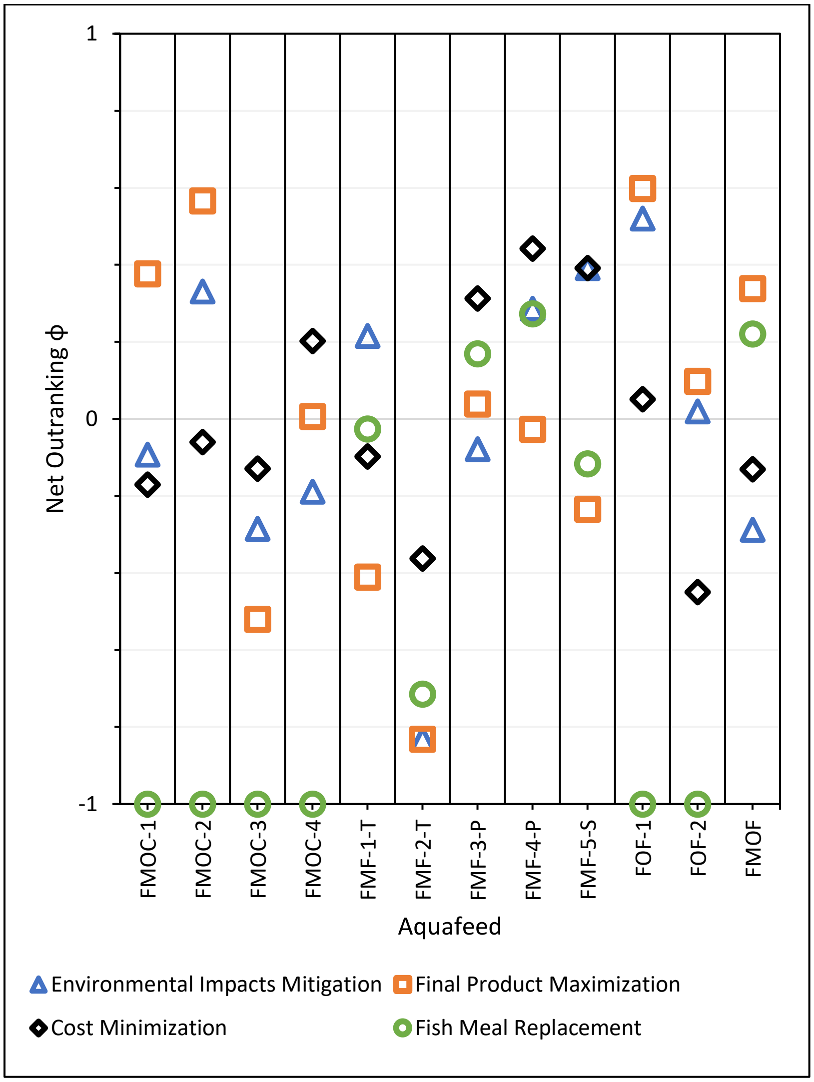

Figure 31. Comparison of MCDA results for different hypothetical scenarios (higher φ value indicates higher desirability).

As shown in Figure 31, in EIM and FPM scenarios, FOF-1 has resulted in the highest net outranking φ values. Therefore, this diet formulation (a diet in which fish oil is replaced by plant-based oil) is the best option for the aquafarmers who are prioritizing either (1) obtaining the most quantity of fish per unit of utilized feed or (2) having the least environmental impacts. In CM and FMR scenarios, FMF-4-P has resulted in the highest net outranking φ values. Thus, FMF-4-P (a diet in which fish meal is replaced by soybean meal) is the best option for the aquafarmers who are prioritizing either (1) using the aquafeed with the least initial cost or (2) replacing the finite fish meal with other alternatives. In contrast, FMF-2-T (a diet in which fish meal is replaced by blood meal) has posed the least net outranking φ values for EIM, FPM, and FMR scenarios. Therefore, the selection of this diet would lead to the most unsought results for the aquafarmers who are seeking to (1) have the least environmental impacts, (2) obtain the most quantity of fish per unit of feed, and (3) replace the finite fish meal with other alternatives. Expectedly, FOF-2 has resulted in the least desirable aquafeed for CM scenario due to the relatively high cost of the utilized algae-based oil (protist based Thraustochytrid oil).

In sum, considering the heterogenity in the surveyed farmers opinions as well as in the hypothetical weightings, and the consequent outranking results (Figures 4 and 6), it is relevant to mention that there is no diet that falls within the “one size fits all” category. The selection of the most suitable aquafeed highly relies on the farmers preference on the relevant characteristics. The prospective scarcity and price increase of marine-based fish meal and fish oil (Froehlich et al., 2018; Hamilton, Newton, Auchterlonie, & Müller, 2020; Sprague, Dick, & Tocher, 2016) is expected to result in further preference of aquafeeds with alternative nutrition resources and lower ecological burdens (Ghamkhar & Hicks, 2020; Glencross, Huyben, & Schrama, 2020). From a decision making perspective, to recognize the most promising alternatives, it is important to integrate the relevant environmental, economic, and technical characteristics and implications of the aquafeeds using alternative ingredients. Our analyses based on the survey-based and hypothetical scenarios indicate that FOF-1 and FMF-4-P are the best fish meal and fish oil replacement strategies among investigated diets. Thereby, the replacement of fish oil by plant-based canola oil and the replacement of fish meal by soy bean meal are potential approaches to obtain desirable aquafeeds (specifically if the fish meal supply becomes limited or expensive). Looking at the alternatives with the least rankings, (FMF-2-T) proposed the least favorability (net φ) in most scenarios. Accordingly, the replacement of fish meal with terrestrial blood meal is not recommended as a potentially desirable alternative, based on this modeling.

6.5. Acknowledgement

This paper is based upon work supported by National Science Foundation (NSF; Funding No. 1942110). The views presented by the authors have not been formally evaluated by NSF, and therefore are reflective for the authors' views only. Any brand name products mentioned are for informational purposes only, and are not an endorsement. The authors gratefully acknowledge the assistance from the farmers, producers and colleagues who have provided feedback, guidance, and inspiration upon the completion of this work.

7. Chapter 7: Spatially Explicit Life Cycle Assessment of Seafood: Comparison of Local vs. Non-Local Provision in Wisconsin

The analysis provided in this chapter is to be submitted for publication, with the anticipated citation of "Ghamkhar, R., Hicks, A. (2021). Spatially Explicit Life Cycle Assessment of Seafood: Comparison of Local vs. Non-Local Provision in Wisconsin." if accepted for publication. Style and formatting modifications have been made for the purpose of this chapter preparation.

Quantification of environmental impacts associated with food transportation is mainly neglected in life cycle assessment and sustainability evaluations of food systems. However, this assumption may neglect a big portion of environmental impacts, especially when comparing local vs. non-local food production systems. Here we perform a comparative environmental impact assessment of seafood provision, using varying local provision scenarios and non-local provision considering transportation differences among different alternatives.

Authorship contribution statement

Ramin Ghamkhar: Designed Research, Performed Research, Analyzed Data, Wrote the Paper.

Andrea L. Hicks: Designed Research, Provided Feedback, Wrote the Paper.

7.1. Main

Since 1961, the average annual increase is the world's fish consumption has outpaced the population growth. In terms of per capita consumption, the annual fish consumption per person has increased from 9.0 kg in 1961 to 20.2 kg in 2018, which represents 124.4% increase of annual per capita fish food consumption worldwide (FAO, 2018). Concerns regarding the environmental sustainability of the seafood supply have also increased in conjunction with the growing consumption (Aubin et al., 2006; d'Orbcastel et al., 2009; Ghamkhar, Hartleb, et al., 2020).

In order to quantitatively evaluate the environmental sustainability of fish consumption, life cycle assessment (LCA) could be utilized throughout the supply chain (seafood production, distribution and aggregation, food processing, marketing, purchasing, preparation and consumption, and waste management and recovery) (Li, Wang, Chan, & Manzini, 2014). However, due to the complexities in the whole chain evaluation, the majority of previous studies have taken the cradle-to-gate approach, in which only the environmental impacts of seafood production stage is assessed (Bibbiani et al., 2018; Bohnes & Laurent, 2019; Matthews, Hendrickson, & Matthews, 2015). In production scenarios that a recirculation system is utilized (e.g. RAS, aquaponics, IMTA), many studies have addressed energy requirements as the major contributor of the environmental impacts (Aubin et al., 2006; Fang et al., 2017; Ghamkhar, Hartleb, et al., 2020; Hindelang et al., 2014; Hollmann, 2017; Liu et al., 2016; Samuel-Fitwi et al., 2013; Silva, Valdés-Lozano, Escalante, & Gasca-Leyva, 2018). Contrarily, in production scenarios that a non-recirculation system is utilized (e.g. flow-through, net pen) feed ingredient production is identified as the main contributor of environmental impacts (Nathan W Ayer & Tyedmers, 2009; Cao, Diana, & Keoleian, 2013; Dekamin et al., 2015; Ghamkhar, Boxman, et al., 2020).

Previous studies have been predominantly focused on either (a) protecting aquatic species (targeted or non-targeted) (Asis, Lacsamana, & Santos, 2016; Farmery, Gardner, Green, & Jennings, 2014; Gwinn et al., 2015; King, 2019; Krantz & Jordan, 1996; Powles et al., 2000) or (b) reducing the ecological impacts (Cooke, Murchie, & Danylchuk, 2011; Farmery et al., 2014; Lackey, 1994; Wu et al., 2019; Yacout et al., 2016) in the production stage. As a result, only a few studies have quantified the impacts associated with transportation in the evaluations (Biermann & Geist, 2019; Henriksson et al., 2017; Jerbi et al., 2012). However, due to the stringent health regulations and quality standards that should be addressed, transportation has a potential to contribute greatly to the overall environmental impacts of fish supply chain, and needs to be fully evaluated (FAO, 2018; Ziegler et al., 2013). Furthermore, the prospective increasing demand for seafood provision is urging us to answer to the question of whether it is more environmentally preferable to produce local, with potential elevated heating needs in a cold-weather (e.g. Wisconsin), or non-local, with potential elevated transportation demands (Ghamkhar, Boxman, et al., 2020).

Here we perform a holistic analysis of the environmental impacts associated with fish food production and transportation offsets with a case study of Wisconsin (Midwest US) as a cold-weather location, undertaking a spatially-explicit approach. First, we evaluate the elevated heating demands associated with local indoor aquaculture at a county-level, using varying space heating scenarios. Second, we evaluate the transportation demand differences, in terms of mode and distance, among local and non-local production, considering scenarios of consumption in most populated cities near Wisconsin (i.e. Chicago, Milwaukee, and Minneapolis). Third, we perform a comparative analysis of the environmental impacts trade-offs, analyzing local and non-local seafood provision alternatives using varying consumption and production scenarios (Figure 32).

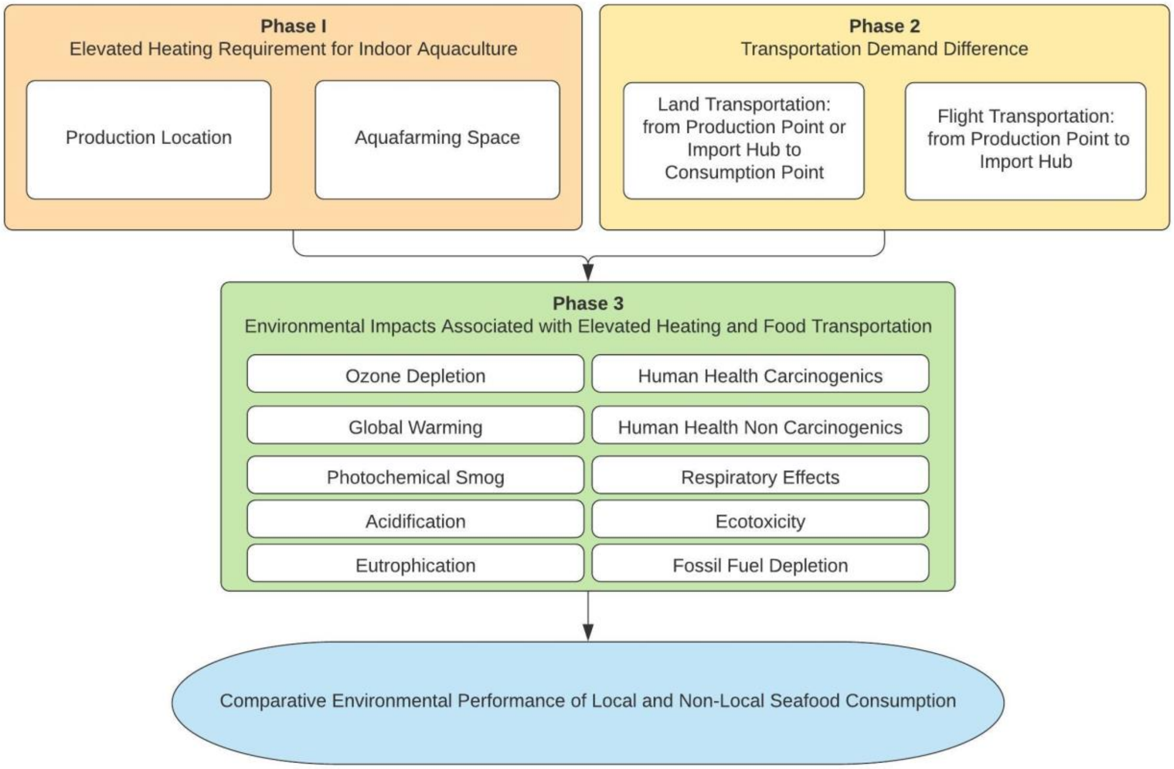

Figure 32. Framework Chart for the Comparative Environmental Performance Evaluation of Local vs. Non-Local Seafood Production.

7.2. Results

We assessed and compared the environmental impacts trade-offs for local vs. non-local seafood provision, considering (1) local production points in all 72 counties of Wisconsin, (2) three practical space heating scenarios (ineffective, semi-effective, and effective), and (3) three consumption points at the three nearest high population cities to Wisconsin (i.e. Chicago, IL; Milwaukee, WI; and Minneapolis, MN).

Phase 1

Due to the relatively low year-round temperature in Wisconsin (Midwest US) compared to other widely known locations for practicing aquaculture, most of the seafood production systems are indoor. Thus, The overall occupied space for indoor aquaculture have a more significant effect on the production system's heating demand (Ghamkhar, Hartleb, et al., 2020). Assuming only an effective heating scenario, in which the total space is optimized and the system is well insulated, will ignore the empirical heating approaches that are currently undertaken for aquafarming (Ghamkhar, Hartleb, et al., 2020; Rakocy et al., 2006). Hence, the heating demands corresponding to ineffective (Scenario 1), semi-effective (Scenario 2) and effective (Scenario 3) space heating are evaluated using a spatially explicit approach (Figure 33).

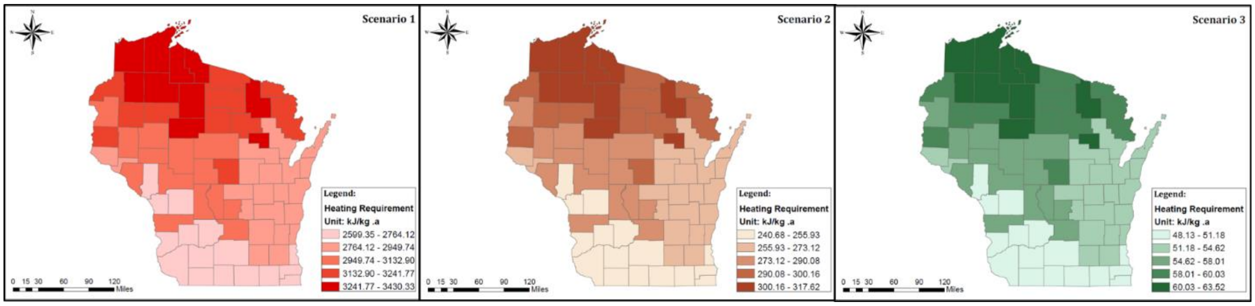

Figure 33. Estimated County-Level Heating Requirements for Indoor Aquaculture. Scenarios represent different annual production capacities in terms of occupied indoor space (overall effective indoor building space per kilogram of live-weight fish produced per year); Scenarios 1, 2, and 3 correspond to the production capacities of 0.54 m^3/kg.a (ineffective), 0.05 m^3/kg.a (semi-effective), and 0.01 m^3/kg.a (effective), respectively.

Figure 33 illustrates that shifting from one scenario to the other regarding total space heating (i.e. scenario 1 vs. scenario 2 vs. scenario 3) results in the change in heating demand by ~1 order of magnitude (2599-3431 kJ/kg .a for scenario 1, 240-318 kJ/kg .a for scenario 2, and 48-64 kJ/kg .a for scenario 3). Whereas, the relative significance of production location impact on heating demand is lower within the state (i.e. higher demands in colder locations, but at the same order of magnitude). This indicates that implementation of effective space heating strategies is of prime importance for practical improvement of systems energy saving, and the reducing the overall production environmental impact.

Phase 2

Land transportation using lorry with reefer is the main approach for seafood in-shore transportation (Ben-Asher et al., 2020; Garrity-Blake & Ware, 2014). To quantify the distance from seafood production points (i.e. counties) or import hub (i.e. Chicago as the closest designated port for perishable items) to consumption points (i.e. nearest populated cities), the driving routes (in km) between all counties and consumption points have been elicited and tabulated (Table E4 of the Appendix). Furthermore, due to (1) the majority of imported seafood to the US being imported from East Asia (e.g. China, Taiwan, Indonesia), and (2) the importance of swift shipment for seafood as a perishable item, flight transportation with reefer is the major approach for fish imports from overseas. We estimate the average distance from seafood production point to the nearest import hub (Chicago port) as 10550.23 km.

Phase 3

We found a significant elevation of environmental impacts (e.g. ~2 orders of magnitude for global warming potential) for non-local seafood provision compared to local seafood provision due to remarkable environmental impacts associated with flight transportation with reefer (Figure 34, Tables E7-E13 of the Appendix).

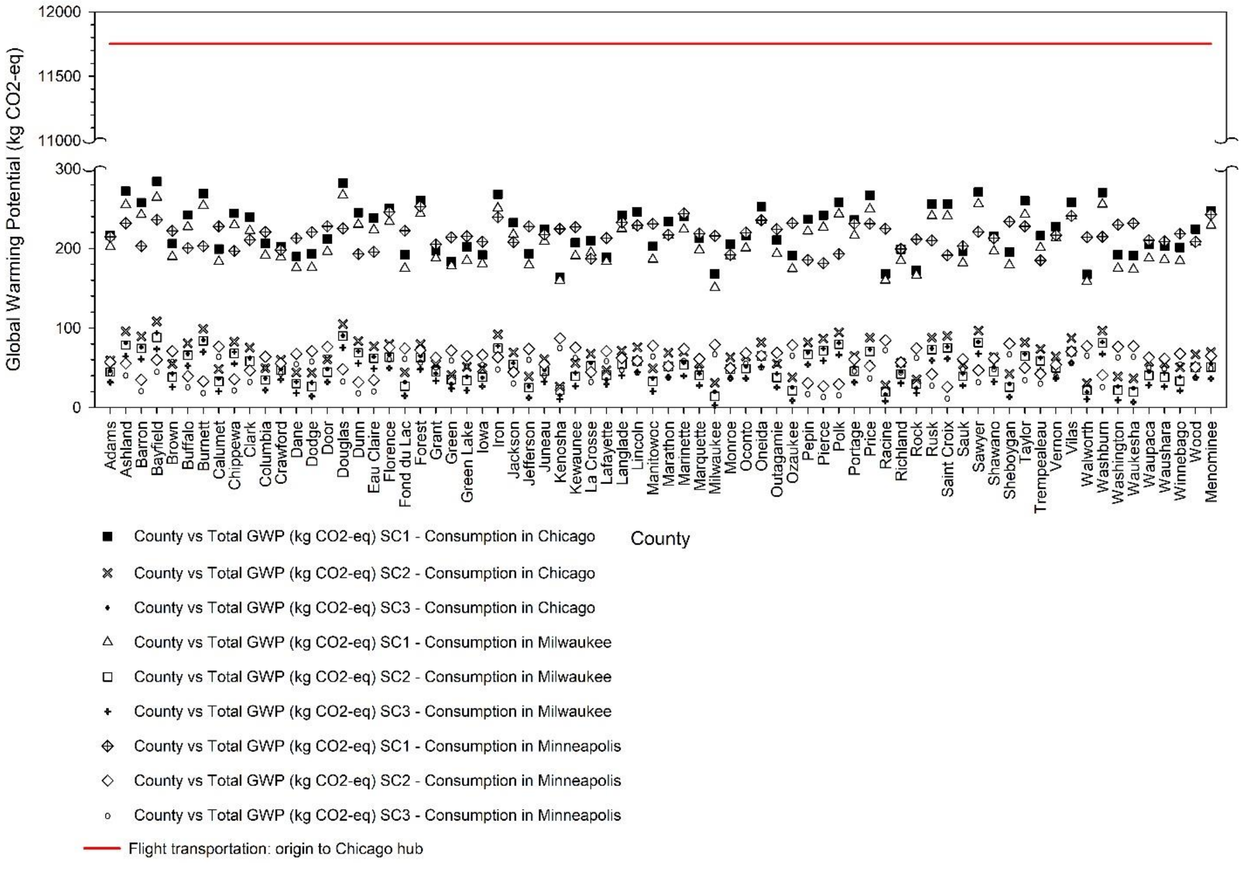

Figure 34. County-level quantification of GWP per ton of fish associated with elevated heating and food transportation using three space heating scenarios (SC1, SC2, and SC3; corresponding to scenario 1 (ineffective), scenario 2 (semi-effective) and scenario 3 (effective)) and three ultimate consumption alternatives (consumption in Chicago, Milwaukee, and Minneapolis).

Delving into the contributing parameters to the overall environmental impacts, we observe that >99% of flight transportation impacts, evaluating GWP and 9 other indicators, are associated to transport rather than operation. Thus, the elevated environmental impacts associated with non-local seafood provision is mainly due to the remarkable distance, and optimization of operational strategies (e.g. refrigeration) is not tangibly mitigating the total environmental impacts.

For local seafood provision, the major contributor to the elevated impacts significantly depends on (1) undertaken heating scenario and (2) ultimate consumption point. For instance, considering the implementation of effective space heating for local seafood provision, land transportation contributes to >81% of elevated GWP, considering all Wisconsin counties as production points and the ultimate consumption in Chicago. However, the contribution of land transportation reduces down to 54%, considering ultimate consumption in Minneapolis and Milwaukee, which have shorter average distance to the production points (neglecting concurrent production and consumption in Milwaukee). We observed similar trends using semi-effective and ineffective space heating, with lower contribution of land transportation to the elevated environmental impacts (as low as 2%).

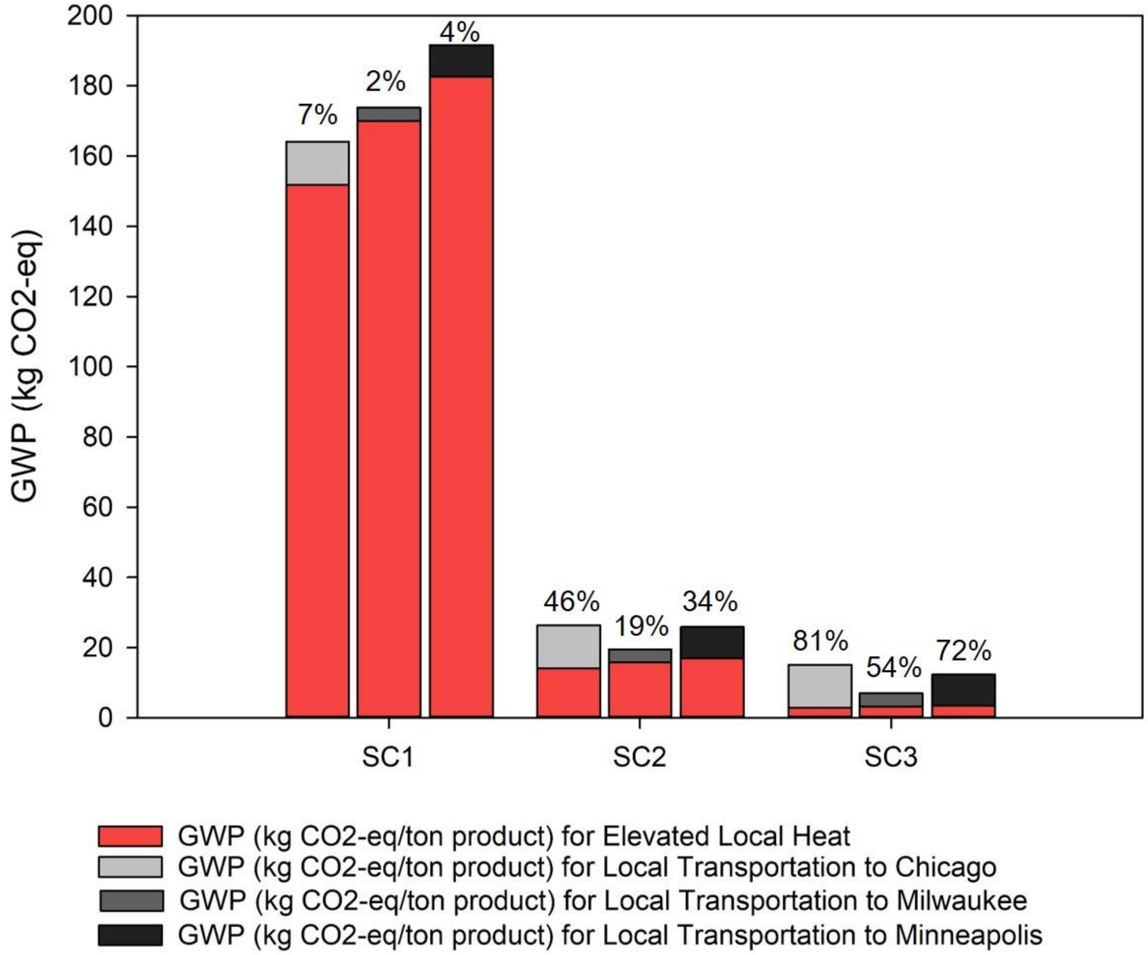

Figure 35. Minimum Elevated GWP from Land Transportation / Overall Elevated GWP from Local Seafood Provision (i.e. elevated heating demand and land transportation). SC1, SC2, and SC3 corresponds to heating scenario 1 (ineffective), scenario 2 (semi-effective) and scenario 3 (effective), respectively.

Despite the significant contribution of both land transportation and elevated heating demand to the local seafood provision environmental impacts, shifting from one heating scenario to the other results in more steep changes in the overall impact contribution of land transportation (e.g. Figure 35) compared to consumption points alterations, highlighting the significance of implementing effective space heating for local seafood provision. Furthermore, in contrast with previous studies, results showcase that the relative elevated environmental impacts of land transportation is beyond to be neglected in most scenarios, as it poses comparable impacts with respect to the environmental impacts associated with elevated heating.

7.3. Discussion

To illustrate the extent of relative environmental performance of local vs. non-local seafood provision, we quantified the distance that a locally produced seafood can be transported, using land transportation, to balance out the higher environmental impacts associated with non-local seafood provision, using GWP as the pivotal impact category and three elevated space heating scenarios for local provision (Ghamkhar, Boxman, et al., 2020) (Figure 36). Flight transportation has significantly higher environmental impacts compared to land transportation (by ~2 orders of magnitude, Tables D6-D7 of the Appendix). Therefore, the elevated environmental impacts, comparing non-local vs. local provision, is estimated as [elevated flight transportation impacts – elevated space heating impacts].

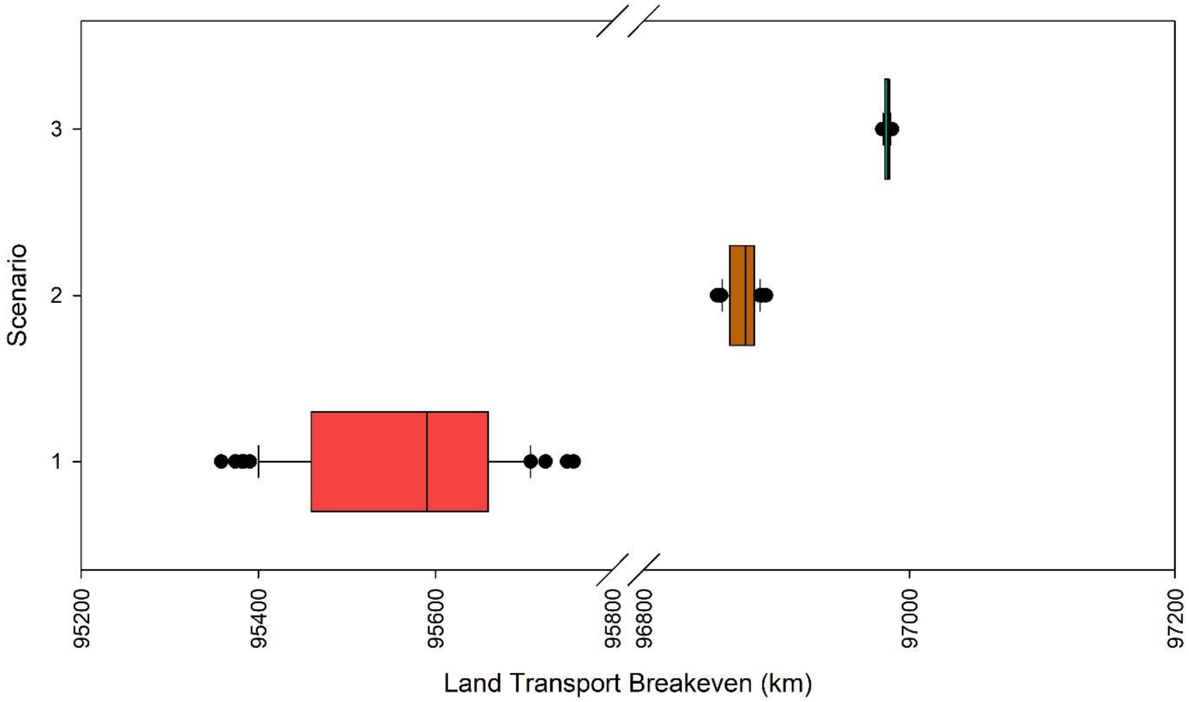

Figure 36. Breakeven analysis of land transportation for local vs. non-local seafood provision using Global Warming Potential (GWP) indicator.

The higher land transport breakeven indicates a longer transportation distance that unit mass (1 ton) of locally produced seafood should travel to offset the GWP associated with unit mass (1 ton) of non-locally produced seafood. The breakeven analysis using all three space heating scenarios (considering 72 counties in Wisconsin as production points) results in land transport breakeven of 95358 to 96987 km, which is ~7.5 times higher than the earth diameter. This highlights the environmental advantage of local seafood provision over non-local seafood provision, even considering a cold-weather location production. Additionally, effective space heating results in at least 1223 km higher land transport breakeven compared to ineffective space heating, which is equivalent to ~0.1 of the earth diameter. This indicates the importance of improving space heating scenarios for local seafood provision in a cold-weather setup to mitigate the environmental impacts of seafood provision.

Currently, the majority of studies on seafood and aquaculture disregard the environmental implications of transportation due to two main reasons; First, studies designed as cradle-to-gate analysis, meaning that the system boundary includes life cycle stages up to the production stage. Second, there is a potential significant variation in the post-farm processes due to lack of reliable data on the ultimate fate of the products (e.g. no commercialization for research-scale systems). Here we found that neglecting the environmental impacts associated to seafood transportation, either land transit or flight, could ignore a significant portion of the total life cycle environmental impacts for seafood provision. Hence, expanding on system boundary to include transportation phases is vital for future studies to provide a comprehensive analysis. Furthermore, we found that the increase in local seafood provision capacity while elevating systems' environmental performance also requires optimized use of space and location. Implementation of systems in the current unused public infrastructure to provide the required indoor environment for year-round production is one potential approach to undertake for capacity increase. However, effective heating techniques based on the infrastructure configurations (e.g. circulation pattern, solar radiation, etc.) need to be executed.

7.4. Conclusion

We identified that local seafood provision, considering (1) all Wisconsin counties as production points, (2) cities of Chicago, Milwaukee, and Minneapolis as consumption points, and (3) effective, semi-effective, and ineffective space heating approaches, has significantly lower environmental impacts than non-local seafood provision, considering flight transportation from offshore production points. The necessity to elevate local seafood production capacity to enhance the environmental sustainability of seafood provision is essential, despite potential elevated heating demands for aquaculture in Wisconsin.

Furthermore, we found that (1) elevated heating demands and (2) land transportation have significant contribution to the elevated local seafood provision environmental impacts based on varying scenarios (Figure 4). In addition, previous research suggests that heating is an environmental impact hotspot in aquaculture, especially in cold-weather regions such as Wisconsin (Ghamkhar, Boxman, et al., 2020; Ghamkhar, Hartleb, et al., 2020). Thus, practical strategies to improve the environmental sustainability of local seafood provision include (1) implementing energy-efficient heating techniques (e.g. effective use of space, passive heating, heater location and configurations), and (2) optimization of seafood consumption and production locations according to prospective local demand and production capacity.

7.5. Methods

Comparative life cycle assessment (LCA) is used as the methodology to evaluate the comparative environmental impacts of seafood provision scenarios (Hu et al., 2020). The specific LCA configurations are described below (ISO-Norm, 2006). Further details such as parameter values for different scenarios and production/consumption points, and data sources are provided as supplementary information (SI) in Appendix E.

7.5.1. Scope and System Boundary

The main goal of this study is to determine the environmental impact tradeoffs between local vs. non local seafood provision, incorporating the impact of transportation. For this purpose, the elevated heating demands due to space heating requirement for local seafood production, considering all counties in Wisconsin as production points, are evaluated using three realistic alternatives. Transportation requirements are also estimated using (1) flight transportation with refrigeration for off-shore transport (2) land transportation with refrigeration for on-shore transport, using (1) all Wisconsin counties as local seafood production points and (2) Chicago, Milwaukee, and Minneapolis as consumption points.

7.5.2. Evaluation Criteria

SimaPro 8.2.0 is used as the modeling platform to quantify the environmental impacts, using databases from EcoInvent3 (EcoInvent, 2014) and USLCI (Norris, 2004). Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) 2.1 (developed by US EPA) is selected for the characterization of environmental impacts. The impact categories evaluated in this study (abbreviation, unit) are ozone depletion potential (ODP, kg CFC-11 eq), global warming potential (GWP, kg CO2 eq), photochemical smog potential (PSP, kg O3 eq), acidification potential (ACP, kg SO2 eq), eutrophication potential (EUP, kg N eq), human health carcinogenics potential (HHCP, CTUh), human health non carcinogenics potential (HHNCP, CTUh), respiratory effects potential (REP, kg PM2.5 eq), ecotoxicity potential (ECP, CTUe), and fossil fuel depletion potential (FFP, MJ surplus). Quantifying the environmental impacts, using multiple impact categories provides the opportunity to have a holistic assessment and to analyze potential tradeoffs in a holistic manner.

7.5.3. Functional Unit

The functional unit for the quantification of elevated environmental impacts is unit mass (1 ton) of fish provision. For example, to quantify the elevated global warming potential (GWP) for local seafood production, considering (1) effective space heating, (2) production point at Dane county, WI, and (3) consumption point at Chicago, IL, total CO2-eq emissions were calculated for elevated heating demands and land transportation per ton of fish provided (32.47 kg CO2-eq).

7.5.4. Heating Demand Estimation

Following the principles of energy transformation through thermal energy ($Q=M.C.\Delta T$), the overall thermal energy gained (or lost) for an indoor space is estimated as a function of temperature difference (indoor vs. outdoor) and overall occupied space ($\rho.V$) (Whitaker, 2013). Higher year-round HDD for a location, corresponds to higher overall temperature difference (ΔT) for the indoor aquaculture system for annual production (J. Chen, 2019). Therefore, counties with colder climates pose higher heating demands at fixed space heating configurations. On the other hand, larger volume (V) of space occupied for indoor aquaculture results in larger mass (M) and elevated space heating demands, and vice versa. In addition, the heat loss is a function of how well insulated the indoor space is. To mimic real-case scenarios, a "well insulated" space (corresponding to an enclosed space, in which walls are erected but not insulated and doors and windows covered with plastic sheeting or tarps) is assumed (Simplex). Overall occupied space per unit of annual seafood production (m^3/kg. a) is estimated based on three realistic scenarios, representing ineffective(Ghamkhar, Hartleb, et al., 2020) (SC1, 0.5 m^3/kg. a), semi-effective(Helfrich & Libey, 2003) (SC2, 0.05 m^3/kg. a), and effective(Walker, 2017) (SC3, 0.01 m^3/kg. a) space usage. Natural gas (combusted at US industrial equipment) is used as the heating source. A conversion of 37631 kJ to 1 m3 natural gas is performed(Deru & Torcellini, 2007).

7.5.5. Transportation Demand Estimation

To estimate the required flight transportation for non-local seafood provision, the average mass-based distance from production point to Chicago port (as the closest designated port for perishable products) is estimated using contribution percentage of total tilapia imported to the US from different countries. The commute distances (flight and route distances) are estimated using an online distance calculator. Land transportation has been elicited using production points (Wisconsin counties) as starting points and consumption points (Chicago, Milwaukee, and Minneapolis) as destinations.

8. Chapter 8: Conclusions and Future Work

8.1. Summary and Contributions

In the first paper (Chapter 2), a comparison of different production systems, with a focus on the differences between intensive land-based systems and extensive pond systems, showed an improvement of overall environmental performance, with a possibility of burden shifting when moving to more intensive aquaculture systems. This literature review demonstrated that while intensive aquaculture systems have greatly reduced negative, local environmental impacts; many negative, global environmental impacts may still remain without applying case-specific mitigation strategies. The achievement of sustainable aquaculture production will likely come from both improved technologies and a careful balance between local and global environmental impacts through management of production intensities.

The second paper (Chapter 3) provided a cradle-to-gate impact assessment is presented for a carnivorous fish producing aquaponic system, located in a cold weather region, in ten impact categories. Heat, electricity, equipment, and fish food are the four environmental impact hotspots of the aquaponic system. The analysis performed in this study emphasizes the importance of applying optimization techniques in order to reduce the environmental impacts associated with the aforementioned impact hotspots. Results suggest that as aquaculture is the fastest growing major food sector in the world, integration of aquaculture and agriculture systems using aquaponics will gain more attention due to their multi-functionality, production intensification in small land area, and reducing overall water consumption and waste emissions to the environment. However, techniques to reduce heat and energy consumption are necessary to be executed in future studies.

In the third paper (Chapter 4), a comprehensive analysis of the environmental impacts of aquafeed production is performed using 12 formulated and tested aquafeeds with different ingredient compositions, including fish meal and oil free diets. As the investigated diets have already been successfully utilized, their practicality is assumed to be promised. However, the environmental implications of investigated aquafeeds have been different in terms of resources use and pollutant emissions. The major findings of this study were: (1) Sole replacement of fish meal (no fish oil replacement) is potentially not effective enough to significantly reduce the use of biotic resources, but the replaced ingredients (poultry meal, soybean meal, and fish trimming by-product) can potentially lower the impacts based on other emission-based and resource-based indicators. (2) Sole replacement of fish oil (no fish meal replacement) can potentially lead to significant decrease in the use of biotic resources. However, technologies regarding substitution methods needs to be improved in order to mitigate the energy use and its associated environmental impacts. And (3) To mitigate the overall environmental impacts of aquafeed production, considering biotic resources, abiotic resources and pollutant emissions, energy-efficient fish oil replacement strategies should be applied in addition to the fish meal replacement by alternatives with lower conventional environmental impacts.

In the fourth paper (Chapter 5), an integrated environmental and economic evaluation of a cold-weather located aquaponic system, considering three operational year-round cycles (tilapia, conventional walleye, and hybrid walleye) was presented. The major finding of this study was: (1) Heat, electricity, aquafeed, and infrastructure were the major contributors of the environmental impacts; (2) Co-production of plants from the aquaponic system was essential to elevate environmental and economic performance. (3) Infrastructure, labor and heat (in terms of costs) were the major economic contributors of the aquaponic system; and (4) Leveraging both environmental and economic evaluations, results suggested that heat and infrastructure were the two key parameters that should be prioritized for optimal usage in the investigated aquaponic system.

The fifth paper (Chapter 6) sought to implement multi criteria decision analysis to evaluate the sustainability of varying formulated aquafeeds (e.g. fish meal and oil free diets) based on their relevant economic, environmental, commercial, and technical characteristics. For this purpose, realistic and hypothetical aquafarmer decision weightings were utilized on a holistic set of formulated aquafeeds. Results suggested that there is no diet that falls within the “one size fits all” category. Our analyses indicated that the replacement of fish oil by plant-based canola oil and the replacement of fish meal by soy bean meal are potential approaches to obtain desirable aquafeeds (specifically if the fish meal supply becomes limited or expensive). Contrarilly, the replacement of fish meal with terrestrial blood meal is not recommended as a potentially desirable alternative, based on this modeling.

In the sixth paper (Chapter 7), a holistic analysis of the environmental impacts associated with fish food production and transportation offsets was conducted, undertaking a spatially-explicit approach. We identified that local seafood provision, considering (1) all Wisconsin counties as production points, (2) cities of Chicago, Milwaukee, and Minneapolis as consumption points, and (3) effective, semi-effective, and ineffective space heating approaches, has significantly lower environmental impacts than non-local seafood provision, considering flight transportation from offshore production points. The necessity to elevate local seafood production capacity to enhance the environmental sustainability of seafood provision is essential, despite potential elevated heating demands for aquaculture in Wisconsin. In addition, we found that neglecting the environmental impacts associated to seafood transportation, either land transit or flight, could ignore a significant portion of the total life cycle environmental impacts for seafood provision. Hence, expanding on system boundary to include transportation phases is vital for future studies to provide a comprehensive analysis.

Overall, this body of work extended the current state of knowledge and discussion, as to whether aquaponics is a sustainable food production approach in a cold weather location. The presented results and discussions are significant to the literature, as it uniquely incorporates a holistic-system-level approach to evaluate different aspects and vulnerabilities in food production systems, focusing on aquaponics, by undertaking potential mitigation strategies including system intensification, system integration, alternative feeding, and local production.

Major innovations of this work include: (1) Holistically evaluating the environmental impacts of US-based cold weather aquaponics systems, which has led to new knowledge about the greatest contributors to the environmental impacts. (2) Evaluating the environmental impacts of alternative aquafeed diets. This has led the generation of new knowledge regarding the tradeoffs of different alternative protein and fatty acid sources, which can inform sourcing. (3) Applying MCDA to aquafeeds with stakeholder inputs, which has created new knowledge as a mathematical analysis of the tradeoffs for various aquafeed formulations; and (4) Analyzing the tradeoff between WI cold weather aquaculture and transportation environmental impacts, which has created new knowledge in the area of local and sustainability of aquaculture.

In addition, this research could serve as a roadmap for future LCAs, especially the ones who aim to evaluate holistically alternative and potential food provision strategies in cold weather locations.

8.2. Future Work

Future work to further expand the body of research on improving the sustainability of aquaculture and aquaponic systems include: (1) The Implications of Scaling-Up Production Systems, (2) Environmental Implications of Using Insects as Aquafeeds Protein Source, and (3) Network Optimization of Production/Consumption Locations.

It is expected that a larger scale operation of food production systems, including aquaculture and aquaponic, would result in mitigated environmental impacts and costs per unit of product. However, as sized-up production tags along with elevated material and energy demands, a meta-analysis of aquaponics and aquaculture systems with varying scales could be performed to evaluate the trade-off points and the scale-up implications of these systems, using (1) a comprehensive and fixed system boundary and (b) comparable inventory parameters, to provide a better estimation. Future research could be centered around evaluating the benefits of these food production systems by accounting net social, environmental, and economic benefits. Moreover, case specific challenges on the industrial-level aquaculture and aquaponic operation, considering different set up factors (e.g. warm-weather vs. cold-weather) could be further investigated.

With respect to aquafeeds production, there is a variety of other novel and promising ingredients that could potentially lead to more sustainable aquafeeds. These alternative ingredients include krill, feather meal, and insect-based meal. For example, black soldier fry is reported to be a nutrient-rich input to provide sustainable protein, following the concept of industrial ecology (i.e. feeding input from the growing animal agriculture waste).

Furthermore, to optimize food transportation demand and its associated environmental impacts, optimization of seafood consumption and production locations according to (1) prospective local demand, (2) travel distances, (4) local elevated heating demand, and (4) local production capacities should be performed and implemented.

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Appendix A

Supplementary Information from Chapter 3.

Table A11. Life cycle inventory of one-year operation of aquaponic system.

Process	Section	Material	Amount	Unit	Database	Comment
One-year Aquaponic system Operation	Input	Fish food	968.365	kg	Measured	Skretting, Europa Co.
		Water	427,188	kg	Inputs from nature/ groundwater	Delaide *et al*. 2017 One-time annual fill + 3% daily water loss
		Electricity	6658	kWh	Measured	Montello Facility Co.
		Heat	3050.3	m^3	USLCI	Natural gas, Deru *et al*. 2007 (kWh to m^3)
		Seed	46.420	g	Agri-footprint - mass allocation	johnnyseeds.com, 1lb = 99200 seeds
		Lab equipment	6	p	Measured	Nelson & Pade
	Outputs	Fish	91.316	kg	Measured	Fillet
		Kale	74.542	kg	Measured	Top of plant
		Butterhead	167.545	kg	Measured	Top of plant
		Pak Choi	376.435	kg	Measured	Top of plant
		Romaine	219.401	kg	Measured	Top of plant
		Fish Waste	248.632	kg	Ecoinvent 3 APOS	Fish except fillet
		Solids waste	242.091	kg	Ecoinvent 3 APOS	Rakocy *et al.* 2007
1 kg Fish food (Skretting, Norway; FMC #1)	input	Fishmeal	0.560	kg	Agri-Footprint – mass allocation	Bjerkeng *et al*. 1997
		Soymeal	0.088	kg	USLCI	Bjerkeng *et al*. 1997
		Capelin Oil	0.219	kg	Agri-Footprint – mass allocation	Bjerkeng *et al*. 1997 Soler-Vila *et.al.* 2009
		Wheat Starch	0.097	kg	Agri-Footprint – mass allocation	Bjerkeng *et al*. 1997 Soler-Vila *et.al.* 2009
1 kWh Energy (2016 resources)	input	Natural gas	0.38	kWh	USLCI	EIA, Alliant Energy
		Coal	0.37	kWh	USLCI	EIA, Alliant Energy
		Nuclear	0.06	kWh	USLCI	EIA, Alliant Energy
		Oil	0.04	kWh	USLCI	EIA, Alliant Energy
		Renewables	0.15	kWh	Calculated	EIA, Alliant Energy
1 kWh Renewables	inputs	Wind	0.64	kWh	ELCD	WASAL
		Solar	0.01	kWh	Ecoinvent 3 APOS	WASAL
		Biomass	0.19	kWh	USLCI	WASAL
		Hydro-electric	0.17	kWh	Ecoinvent 3 APOS	WASAL
1 lab equipment	inputs	Fish tanks	4.115	kg	Ecoinvent 3 APOS	Assmann Co.,

(modified based on one-year operation)		Clarifiers	1.402	kg	Ecoinvent 3 APOS	Polytank Co., HDPE material acquisition & manufacturing (injection moulding)
		Mineralization tanks	1.402	kg	Ecoinvent 3 APOS	
		Degas tanks	0.301	kg	Ecoinvent 3 APOS	
		Raft tanks	2.805	kg	Ecoinvent 3 APOS	
		Sump tank	0.197	kg	Ecoinvent 3 APOS	
		Rockwool grow cubes	9.422	kg	ELCD	Nelson & Pade Inc.
		Raft trays	1.083	kg	ELCD	Expanded polystyrene (EPS), Granulate production
		Fishnets	0.045	kg	Ecoinvent 3 APOS	Nylon production and manufacturing (extrusion)
		Water Pump	1/7	p	Ecoinvent 3 APOS	Nelson & Pade Inc.
		Lights	2	p	Ecoinvent 3 APOS	Nelson & Pade Inc.

Table A12. Alternative fish food productions inventory.

Process	Section	Material	Amount	Unit	Database	Comment
1 kg fishmeal-free food #1 (FMF #1)	Input	Poultry meal	0.295	kg	Agri-Footprint – mass allocation	Schmidt *et al.* 2016
		Wheat flour	0.099	kg	Agri-Footprint – mass allocation	Schmidt *et al.* 2016
		Fish oil	0.182	kg	Agri-Footprint – mass allocation	Schmidt *et al.* 2016
1 kg fishmeal-free food #2 (FMF #2)	Input	Soybean meal	0.450	kg	Agri-Footprint – mass allocation	Rawles *et al.* 2013
		Poultry meal	0.131	kg	Agri-Footprint – mass allocation	Rawles *et al.* 2013
		Corn	0.100	kg	Agri-Footprint – mass allocation	Rawles *et al.* 2013
		Wheat starch	0.087	kg	Agri-Footprint – mass allocation	Rawles *et al.* 2013
		Fish oil	0.100	kg	Agri-Footprint – mass allocation	Rawles *et al.* 2013
1 kg Tilapia food (FMC #2)	input	Soybean meal	0.400	kg	Agri-Footprint – mass allocation	Boxman *et al.* 2015
		Wheat middlings	0.171	kg	Agri-Footprint – mass allocation	Boxman *et al.* 2015
		Maize/ Corn	0.171	kg	Agri-Footprint – mass allocation	Boxman *et al.* 2015
		Fish meal	0.057	kg	Agri-Footprint – mass allocation	Boxman *et al.* 2015
1 kg Cobia food (FMC #3)	input	Fishmeal	0.450	kg	Agri-Footprint – mass allocation	Zhou *et al.* 2004
		Defatted soybean meal	0.100	kg	Ecoinvent 3 – allocation at point of substitution - unit	Zhou *et al.* 2004
		Peanut meal	0.090	kg	Ecoinvent 3 – allocation at point of substitution - unit	Zhou *et al.* 2004
		Wheat flour	0.227	kg	Agri-Footprint – mass allocation	Zhou *et al.* 2004
		Fish oil	0.020	kg	Agri-Footprint – mass allocation	Zhou *et al.* 2004
		Soy oil	0.020	kg	USLCI	Zhou *et al.* 2004

Table A13. Other electricity resource scenarios

Process	Section	Material	Amount	Unit	Database	Comment
1 kWh Energy (resources for 2005)	Input	Natural gas	0.37	kWh	USLCI	EIA, Alliant Energy
		Coal	0.44	kWh	USLCI	EIA, Alliant Energy
		Nuclear	0.09	kWh	USLCI	EIA, Alliant Energy
		Oil	0.05	kWh	USLCI	EIA, Alliant Energy
		Renewables	0.05	kWh	Calculated (renewable resources)	EIA, Alliant Energy
1 kWh Energy (resources for 2024, to be achieved)	Input	Natural gas	0.43	kWh	USLCI	EIA, Alliant Energy
		Coal	0.22	kWh	USLCI	EIA, Alliant Energy
		Nuclear	0.05	kWh	USLCI	EIA, Alliant Energy
		Oil	0.01	kWh	USLCI	EIA, Alliant Energy
		Renewables	0.29	kWh	Calculated (renewable resources)	EIA, Alliant Energy

Table A14. Other equipment lifespan scenarios.

Process	Section	Material	Amount	Unit	Database	Comment
1 lab equipment (5-year operation)	Input	Fish tanks	16.463	kg	Ecoinvent 3 APOS	Assmann Co., Polytank Co., HDPE material acquisition & manufacturing (injection moulding)
		Clarifiers	5.611	kg	Ecoinvent 3 APOS	
		Mineralization tanks	5.611	kg	Ecoinvent 3 APOS	
		Degas tanks	1.205	kg	Ecoinvent 3 APOS	
		Raft tanks	11.222	kg	Ecoinvent 3 APOS	
		Sump tank	0.789	kg	Ecoinvent 3 APOS	
		Rockwool grow cubes	9.422	kg	ELCD	Nelson & Pade Inc., Basalt mining and subsequent modification
		Raft trays	1.083	kg	ELCD	Expanded polystyrene (EPS), Granulate production
		Fishnets	0.181	kg	Ecoinvent 3 APOS	Nylon production and manufacturing (extrusion)
		Water Pump	1/7	p	Ecoinvent 3 APOS	Nelson & Pade Inc.
		Lights	2	p	Ecoinvent 3 APOS	Nelson & Pade Inc.
1 lab equipment (3-year operation)	Input	Fish tanks	27.438	kg	Ecoinvent 3 APOS	Assmann Co., Polytank Co., HDPE material acquisition & manufacturing
		Clarifiers	9.351	kg	Ecoinvent 3 APOS	
		Mineralization tanks	9.351	kg	Ecoinvent 3 APOS	
		Degas tanks	2.009	kg	Ecoinvent 3 APOS	
		Raft tanks	18.703	kg	Ecoinvent 3 APOS	

	Sump tank	1.315	kg	Ecoinvent 3 APOS	(injection moulding)
	Rockwool grow cubes	9.422	kg	ELCD	Nelson & Pade Inc.
	Raft trays	1.083	kg	ELCD	Expanded polystyrene (EPS), Granulate production
	Fishnets	0.302	kg	Ecoinvent 3 APOS	Nylon production and manufacturing (extrusion)
	Water Pump	1/7	p	Ecoinvent 3 APOS	Nelson & Pade Inc.
	Lights	2	p	Ecoinvent 3 APOS	Nelson & Pade Inc.

Table A15. Aquaponic system apparatus description for each lab (out of six existing labs) at UW- Stevens Point Aquaponics Innovation Center.

Equipment*	Quantity	Lifespan (year)	Volume** (gal)	Depth** (in.)	Diameter** (in.)	Thickness ** (in.)	Total Weights (kg)	Share of one-year operation
Fish Tank	2	20	450	52	52	0.312	82.315	4.115 kg
Clarifier	2	20	130	32	36	0.25	28.055	1.402 kg
Mineralization Tank	2	20	80	48	24	0.25	28.055	1.402 kg
Degas Tank	1	20	52	30	22	0.187	6.027	0.301 kg
Raft Tank	4	20	130	32	36	0.25	56.110	2.805 kg
Sump Tank	1	20	25	24	18	0.187	3.945	0.197 kg
Rockwool grow cubes	4	1/8	N/A	N/A	N/A	N/A	1.178	9.422 kg
Raft Tray	4	3	0.825	2	N/A	N/A	3.249	1.083
Fish nets	2	20	N/A	N/A	N/A	N/A	0.906	0.045 kg
Pump	1	7	N/A	N/A	N/A	N/A	N/A	0.143 p
lights	2	1	N/A	N/A	N/A	N/A	N/A	2 p

**Diffusers and inline heater/chiller are excluded from the calculations.*

***Tanks dimensions are obtained from https://polytankco.com, High Density Poly Ethylene (HDPE) density = 0.947 g/cm^3, Expanded polystyrene (EPS) density = 1.04 g/cm^3.*

Table A16. TRACI Environmental Impacts of system contributors based on 1 kg production of fish fillet.

Impact Category	Unit	Fish food	Seeds	Electricity	Heat	Equipment	Fish waste	Solid waste	Total
Ozone depletion	kg CFC-11 eq	1.11E-07	5.63E-13	1.96E-09	5.76E-11	1.68E-07	9.48E-09	2.03E-08	3.11E-07
Global warming	kg CO2 eq	9.16294	8.43E-05	52.59962	80.29579	3.578104	0.119028	0.236988	145.9926
Smog	kg O3 eq	1.384091	9.74E-07	3.130366	1.737983	0.155177	0.004141	0.018665	6.430424
Acidification	kg SO2 eq	0.052197	1.69E-06	0.433525	0.687015	0.016946	0.005134	0.002865	1.197683
Eutrophication	kg N eq	0.006617	3.52E-06	0.005895	0.006734	0.005995	0.000337	0.002934	0.028516
Carcinogenics	CTUh	2.01E-08	2.51E-12	1.57E-07	3.37E-07	2.42E-07	9.02E-09	4.28E-08	8.09E-07
Non carcinogenics	CTUh	3.34E-07	1.37E-09	2.17E-06	4.38E-06	6.2E-06	1.59E-08	1.99E-07	1.33E-05
Rspiratory effects	kg PM2.5 eq	0.003524	6.03E-08	0.022546	0.040536	0.002674	0.000158	0.000146	0.069584
Ecotoxicity	CTUe	6.541084	0.001407	37.80135	107.5889	19.43391	0.598547	9.446453	181.4117
Fossil fuel depletion	MJ surplus	14.65538	2.72E-05	63.37693	210.4531	9.874534	0.088782	0.187128	298.6359

Table A17. Sensitivity analysis results based on +/- 20% inputs change for different impact contributors of the aquaponic system. Reported numbers are sensitivity factors (SFs).

IC	OD	GW	PS	AC	EU	HHC	HHNC	RE	EC	FF
Seeds	3.019E-07	9.619E-08	2.525E-08	2.349E-07	2.060E-05	5.173E-07	1.717E-05	1.445E-07	1.293E-06	1.516E-08
Fish food	5.943E-02	1.046E-02	3.587E-02	7.264E-03	3.867E-02	4.133E-03	4.184E-03	8.441E-03	6.009E-03	8.179E-03
Capital equipment	9.018E-02	4.085E-03	4.022E-03	2.358E-03	3.504E-02	4.996E-02	7.772E-02	6.406E-03	1.785E-02	5.511E-03
Electricity	1.048E-03	6.005E-02	8.113E-02	6.033E-02	3.445E-02	3.240E-02	2.718E-02	5.400E-02	3.473E-02	3.537E-02
Heat	3.089E-05	9.167E-02	4.505E-02	9.560E-02	3.936E-02	6.950E-02	5.487E-02	9.709E-02	9.884E-02	1.175E-01
Fish waste	5.080E-03	1.359E-04	1.073E-04	7.145E-04	1.971E-03	1.858E-03	1.992E-04	3.793E-04	5.499E-04	4.955E-05
Solid waste	1.089E-02	2.705E-04	4.838E-04	3.986E-04	1.715E-02	8.818E-03	2.492E-03	3.485E-04	8.679E-03	1.044E-04

Table A18. Sensitivity analysis results based on +/- 20% inputs change for different fish food ingredients. Reported numbers are sensitivity factors (SFs).

Fish Food	Ingredients\Impact category	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenic	Non carcinogenic	Respiratory effects	Ecotoxicity	Fossil fuel depletion
Fishmeal-free food #1	Poultry meal	0.126	0.145	0.084	0.149	0.148	0.156	0.156	0.139	0.153	0.107
	Wheat flour	0.009	0.003	0.003	0.005	0.016	0.007	0.010	0.005	0.014	0.005
	Fish oil	0.032	0.018	0.079	0.012	0.002	0.003	0.000	0.022	0.000	0.055
Fishmeal-free food #2	Soybean	0.108	0.049	0.065	0.045	0.113	0.137	0.085	0.086	0.094	0.049
	Poultry meal	0.041	0.097	0.038	0.102	0.050	0.028	0.079	0.064	0.066	0.066
	Corn	0.000	0.003	0.019	0.007	0.000	0.000	0.000	0.003	0.003	0.004
	Wheat starch	0.004	0.002	0.001	0.002	0.003	0.001	0.002	0.002	0.003	0.005
	Fish oil	0.013	0.015	0.044	0.010	0.001	0.001	0.000	0.012	0.000	0.042
Cobia food	Fish meal	0.074	0.100	0.133	0.075	0.010	0.008	0.004	0.081	0.002	0.130
	Soybean	0.018	0.008	0.005	0.004	0.004	0.011	0.010	0.011	0.010	0.004
	Peanut	0.051	0.034	0.016	0.049	0.079	0.129	0.013	0.050	0.050	0.013
	Wheat flour	0.020	0.018	0.006	0.033	0.073	0.018	0.139	0.020	0.103	0.012
	Fish oil	0.004	0.005	0.006	0.004	0.000	0.000	0.000	0.004	0.000	0.006
	Soy oil	0.000	0.002	0.002	0.002	0.000	0.000	0.001	0.001	0.002	0.001
Tilapia food	Soybean protein concentrate	0.143	0.149	0.123	0.077	0.087	0.123	0.091	0.085	0.087	0.131
	Wheat flour	0.011	0.005	0.005	0.021	0.024	0.007	0.010	0.019	0.032	0.007
	Maize flour	0.005	0.009	0.018	0.061	0.056	0.036	0.065	0.050	0.048	0.014
	Fish meal	0.007	0.004	0.021	0.008	0.001	0.001	0.000	0.013	0.000	0.014
Skretting	Fish meal	0.104	0.109	0.113	0.107	0.079	0.092	0.032	0.111	0.015	0.112
	Fish oil	0.044	0.046	0.048	0.046	0.034	0.039	0.014	0.047	0.006	0.048
	Soy meal	0.004	0.008	0.005	0.009	0.002	0.015	0.020	0.005	0.069	0.004
	Wheat starch	0.015	0.004	0.001	0.005	0.052	0.020	0.101	0.003	0.076	0.003

Table A19. TRACI Environmental Impacts of system contributors according to different functional units (production of 1 kg fish fillet, 1 kg edible plant top, and 1 kg production based on mass ratio).

Impact Category	Unit	1 kg fish fillet	1 kg edible plant top	1 kg product
Ozone depletion	kg CFC-11 eq	3.11E-07	3.39E-08	3.06E-08
Global warming	kg CO2 eq	145.9926	15.91012	14.34775
Smog	kg O3 eq	6.430424	0.700781	0.631964
Acidification	kg SO2 eq	1.197683	0.130522	0.117705
Eutrophication	kg N eq	0.028516	0.003108	0.002802
Carcinogenics	CTUh	8.09E-07	8.82E-08	7.95E-08
Non carcinogenics	CTUh	1.33E-05	1.45E-06	1.31E-06
Rspiratory effects	kg PM2.5 eq	0.069584	0.007583	0.006839
Ecotoxicity	CTUe	181.4117	19.77006	17.82864
Fossil fuel depletion	MJ surplus	298.6359	32.54504	29.34912

Appendix B

Supplementary Information from Chapter 4.

Table B20. Diet formulation inventory for FMOC-1.

	Section	Material	Amount	Unit	Corresponding LCI	Database	Assumptions / Comments	Reference
1 kg FMOC-1	Input	Poultry Meal	160	g	Chicken co-product, other, at slaughterhouse/NL Mass	Agri-footprint	Chicken meat production co-product mass allocation: 13.76% Trophic Level = 2.21 (Bonhommeau et al., 2013; Duarte et al., 2009)	(John Davidson et al., 2016)
		Wheat Flour	195.1	g	Wheat flour, from dry milling, at plant/UK Mass	Agri-footprint	0.46 g C/g ingredient	
		Menhaden Meal	195	g	Fish meal, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 0.22 (Davis, 2015; M. R. Hasan & Halwart, 2009) Trophic Level = 2.4 (Menhaden)	
		Fish Oil (whitefish Trimming oil)	0	g	Fish oil, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Fish oil by-products mass allocation: 35% (Ytrestøyl, Aas, & Åsgård, 2015)	
		Fish Oil (menhaden)	157.4	g	Fish oil, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 2% (M. R. Hasan & Halwart, 2009) Trophic Level = 2.4 (Menhaden)	
		Soy Protein Concentrate	128.5	g	Soy protein concentrate, consumption mix, at feed compound plant/NL Mass	Agri-footprint	Yield = 0.75% (Erickson, 2015)	
		Blood Meal	70.5	g	Blood meal, spray dried, consumpton mix, at feed compound plant/NL Mass	Agri-footprint	Production from cows, pigs and chicken (spray dried), mass allocation: 18% Trophic Level = 2.21	

							(Bonhommeau et al., 2013; Duarte et al., 2009)	
		Canola Oil	56.5	g	Rape oil, crude {RoW}| rape oil mill operation | APOS, U	Ecoinvent 3	60% contented oil extraction yield (Citeau, Slabi, Joffre, & Carré, 2018)	
		Corn Protein Concentrate	0	g	Protein feed, 100% crude {RoW}| maize grain to generic market for energy feed | APOS, U	Ecoinvent 3	Yield = 0.75% (Erickson, 2015)	
		Dicalcium phosphate	5	g	Triple superphosphate, as 80% Ca(H2PO4)2 (NPK 0-48-0), at plant/RER Mass	Agri-footprint	Micro minerals have zero external biotic resource use	
		Vitamin Premixg	10	g	Ascorbic acid {RoW}| ascorbic acid production | APOS, U	Ecoinvent 3	Vitamins have zero external biotic resource use	
		Lysine-HCL	6.5	g	Glycine {RoW}| market for | APOS, U	Ecoinvent 3	Additional amino acids have zero external biotic resource use	
		Choline CL	6	g				
		Taurine	0	g				
		DL-Methionine	4	g				
		Stay-C	2	g	Ascorbic acid {RoW}| ascorbic acid production | APOS, U	Ecoinvent 3	Vitamins have zero external biotic resource use	
		Threonine	1.5	g	Glycine {RoW}| market for | APOS, U	Ecoinvent 3	Additional amino acids have zero external biotic resource use	
		Trace Minerals Premix	1	g	Iron(III) sulfate, without water, in 12.5% iron solution state {CA-QC}| production | APOS, U	Ecoinvent 3	12.5% solution, Trace minerals have zero external biotic resource use	
		Astaxanthin (Dye)	1	g	Dinitroaniline-compound {RoW}| production | APOS, U	Ecoinvent 3	Food coloring have zero external biotic resource use	

Table B21. Diet formulation inventory for FMOC-2.

	Section	Material	Amount	Unit	Corresponding LCI	Database	Assumptions / Comments	Reference
1 kg FMOC-2	Input	Fish meal	250	g	Fish meal, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 0.22 (Barlow, 2003; M. R. Hasan & Halwart, 2009) Trophic Level = 2.4 (Menhaden)	(Carter et al., 2003)
		Soybean meal	56.2	g	Soybean meal {US}| soybean meal and crude oil production | APOS, U	Ecoinvent 3	0.528 g C/g ingredient	
		Casein	143.2	g	Protein feed, 100% crude GLO | skimmed milk, from cow milk to generic market for protein feed | APOS, U	Ecoinvent 3	Zero external biotic resource use Concentrated protein from skimmed milk (butter production)	
		Wheat Gluten	100	g	Wheat gluten feed, from wet milling, at plant/UK Mass	Agri-footprint	14% gluten content 3.286 g C/g ingredient	
		Canola oil	78.2	g	Rape oil, crude {RoW}| rape oil mill operation | APOS, U	Ecoinvent 3	60% contented oil extraction yield (Citeau et al., 2018) 1.012 g C/g ingredient	
		Fish oil	91.4	g	Fish oil, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 2% (M. R. Hasan & Halwart, 2009) Trophic Level = 2.4 (Menhaden)	
		Thraustochytrid meal	0	g	Created (Table S3)	N/A*	N/A*	
		Pregelatinized starch	136.2	g	Wheat starch slurry, from wet milling, at plant/UK Mass	Agri-footprint	0.46 g C / g ingredient	
		Vitamin mix	3	g		Ecoinvent 3		

		Stay C	3	g	Ascorbic acid {RoW}| ascorbic acid production | APOS, U		Vitamins have zero external biotic resource use	
		Choline CL	2	g	Glycine {RoW}| market for | APOS, U	Ecoinvent 3	Additional amino acids have zero external biotic resource use	
		Mineral mix	5	g	Iron(III) sulfate, without water, in 12.5% iron solution state {CA-QC}| production | APOS, U	Ecoinvent 3	12.5% solution Trace minerals have zero external biotic resource use	
		Calsium phosphate	21.8	g	Triple superphosphate, as 80% Ca(H2PO4)2 (NPK 0-48-0), at plant/RER Mass	Agri-footprint	Micro minerals have zero external biotic resource use	
		Cellulose	50	g	Cellulose fibre, inclusive blowing in (Tchobanoglous, Theisen, & Vigil)| market for | APOS, U	Ecoinvent 3	0.444 g C / g ingredient	
		Bentonite	49	g	Iron(III) sulfate, without water, in 12.5% iron solution state {CA-QC}| production | APOS, U	Ecoinvent 3	Trace mineral 12.5% solution zero external biotic resource use	
		CMC (Carboxymethyl Cellulose)	9	g	Carboxymethyl cellulose, powder (Tchobanoglous et al.)| market for | APOS, U	Ecoinvent 3	0.399 g C / g ingredient	
		Cholestane	1	g	Fatty acid (Tchobanoglous et al.)| market for | APOS, U	Ecoinvent 3	Cholesterol has zero external biotic resource use	
		Yttrium oxide	1	g	Iron(III) sulfate, without water, in 12.5% iron solution state {CA-QC}| production | APOS, U	Ecoinvent 3	Trace mineral 12.5% solution zero external biotic resource use	

* N/A: Not Applicable

Table B22. Input materials and energy required to produce Thraustochytrid meal.

	Section	Material	Amount	Unit	Corresponding LCI	Database	Comments	Reference
100 gr Thraustochytrid meal	Input (meal production)	Glucose	155	g	GLO | market for glucose | APOS, U	Ecoinvent V3	3.23 g.L^{-1} biomass 5 g.L^{-1} glucose	Byreddy, 2015
		Electricity	47.52	MJ	At grid, US 2010/kWh/RNA	USLCI	Freeze drying	
		Electricity	5.28	MJ	At grid, US 2010/kWh/RNA	USLCI	Other (autoclave and centrifugation)	
	Input (lipid extraction)	Methanol	1584	g	GLO | production | APOS, U	Ecoinvent V3	Based on the reported fraction. dry biomass: methanol: chloroform = 50 mg: 1 ml (ρ=792 g.L^{-1}): 2 ml (ρ=1490 g.L^{-1}), Yield = 22%, Extraction process is excluded (Feeding ingredient is the produced lipid).	
		Chloroform	5960	g	GLO | production | APOS, U	Ecoinvent V3		

Table B23. Diet formulation inventory for FMOC-3.

	Section	Material	Amount	Unit	Corresponding LCI	Database	Assumptions / Comments	Reference
1 kg FMOC-3	Input	Fish meal	108	g	Fish meal, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 0.22 (Barlow, 2003(M. R. Hasan & Halwart, 2009)) Trophic Level = 2.4 (Menhaden)	(Akiyama, 1990)
		Soybean meal	450	g	Soybean meal {US}| soybean meal and crude oil production | APOS, U	Ecoinvent 3	0.528 g C/g ingredient	
		Wheat pollards	126	g	Wheat flour, from dry milling, at plant/UK Mass	Agri-footprint	From flour milling of grain, mass allocation: 73.59%	
		Rice bran	200	g	Rice bran meal, solvent extracted, from rice bran	Agri-footprint	0.444 g C / g ingredient	

					oil production, at plant/CN Mass			
		Dicalcium phosphate	46	g	Triple superphosphate, as 80% Ca(H2PO4)2 (NPK 0-48-0), at plant/RER Mass	Agri-footprint	Micro minerals have zero external biotic resource use	
		Fish oil	18	g	Fish oil, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 2% (Ytrestøyl et al., 2015) Trophic Level = 2.4 (Menhaden)	
		Methionine	2	g	Glycine {RoW} | market for | APOS, U	Ecoinvent 3	Additional amino acids have zero external biotic resource use	
		Limestone	24	g	Limestone, at mine/US	USLCI	Limestone mining have zero external biotic resource use	
		Vitamin/Mineral premix	26	g	Ascorbic acid {RoW}| ascorbic acid production | APOS, U	Ecoinvent 3	Vitamins have zero external biotic resource use	

	Section	Material	Amount	Unit	Corresponding LCI	Database	Assumptions / Comments	Reference
1 kg FMOC-4	Input	Soy protein concentrate	190	g	Soy protein concentrate, consumption mix, at feed compound plant/NL Mass	Agri-footprint	Papatryphon et al., 2004 Yield = 0.75% (Erickson, 2015)	(Aas et al., 2019)
		Wheat gluten	90	g	Wheat gluten feed, from wet milling, at plant/UK Mass	Agri-footprint	14% gluten content 3.286 g C/g ingredient	
		Corn gluten	36	g	Maize gluten meal, from wet milling (gluten drying), at plant/US Mass	Agri-footprint	Maize starch prodution by-product Mass allocation: 5.71%	

		Vegetable protein (other resources)	86	g	Vegetable oil, refined GLO| market for | APOS, U	Ecoinvent 3	60% contented oil extraction yield (Citeau et al., 2018)	
		Rapeseed oil	201	g	Rape oil, crude {RoW}| rape oil mill operation | APOS, U	Ecoinvent 3	40% contented oil extraction yield (Pahl, 2008)	
		Wheat starch	89	g	Wheat starch slurry, from wet milling, at plant/UK Mass	Agri-footprint	(Papatryphon et al., 2004)	
		marine protein, forage	117	g	Fish meal, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 0.22 (Barlow, 2003(M. R. Hasan & Halwart, 2009)) Trophic Level = 2.4 (Menhaden)	
		marine protein, trimming	28	g	Fish meal, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Fish meal co-products mass allocation: 35% (Aas et al., 2019)	
		fish oil, forage	78	g	Fish oil, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 2% (M. R. Hasan & Halwart, 2009; Ytrestøyl et al., 2015) Trophic Level = 2.4 (Menhaden)	
		fish oil, trimming	26	g	Fish oil, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Fish oil co-products mass allocation: 35% (Aas et al., 2019)	
		Vitamins, minerals, amino acids, etc.	40	g	Glycine (Tchobanoglous et al.)| market for | APOS, U	Ecoinvent 3	Additional amino acids have zero external biotic resource use	

Table B24. Diet formulation inventory for FMF-1-T.

	Section	Material	Amount	Unit	Corresponding LCI	Database	Assumptions / Comments	Reference
1 kg FMF-1-T	Input	Menhaden meal	0	g	Fish meal, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 0.22 (Barlow, 2003) Trophic Level = 2.4 (Menhaden)	(Rossi Jr & Davis, 2012)
		Poultry meal	147	g	Chicken co-product, other, at slaughterhouse/NL Mass	Agri-footprint	Chicken meat production co-product mass allocation: 13.76% Trophic Level = 2.21 (Bonhommeau et al., 2013; Duarte et al., 2009)	
		Soybean meal	500	g	Soybean meal {US}| soybean meal and crude oil production | APOS, U	Ecoinvent 3	0.528 g C/g ingredient	
		Menhaden oil	51.5	g	Fish oil, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 2% (M. R. Hasan & Halwart, 2009; Ytrestøyl et al., 2015) Trophic Level = 2.4 (Menhaden)	
		Corn starch	53.8	g	Maize starch {RoW}| production | APOS, U	Ecoinvent 3	0.465 g C/g ingredient	
		Whole wheat	160	g	Wheat flour, from dry milling, at plant/UK Mass	Agri-footprint	0.460 g C/g ingredient	
		Corn gluten meal	50	g	Maize gluten meal, from wet milling (gluten drying), at plant/US Mass	Agri-footprint	Maize starch prodution by-product Mass allocation: 5.71%	
		Lecithin	10	g	Soybean lecithin, from crushing (solvent), at plant/UK Mass	Agri-footprint	56% oil extraction yield, 0.942 g C/g ingredient	
		Mineral premix	2.5	g	Iron(III) sulfate, without water, in 12.5% iron solution state {CA-QC}| production | APOS, U	Ecoinvent 3	12.5% solution Trace minerals have zero external biotic resource use	

		Vitamin premix	5	g	Ascorbic acid {RoW}| ascorbic acid production | APOS, U	Ecoinvent 3	Vitamins have zero external biotic resource use	
		Choline Cl	2	g	Glycine {RoW}| market for | APOS, U	Ecoinvent 3	Additional amino acids have zero external biotic resource use	
		Stay C	1	g	Ascorbic acid {RoW}| ascorbic acid production | APOS, U	Ecoinvent 3	Vitamins have zero external biotic resource use	
		CaPO4	16	g	Triple superphosphate, as 80% Ca(H2PO4)2 (NPK 0-48-0), at plant/RER Mass	Agri-footprint	Micro minerals have zero external biotic resource use	
		Dl-methionine	1.2	g	Glycine {RoW}| market for | APOS, U	Ecoinvent 3	Additional amino acids have zero external biotic resource use	

Table B25. Diet formulation inventory for FMF-2-T.

	Section	Material	Amount	Unit	Corresponding LCI	Database	Assumptions / Comments	Reference
1 kg FMF-2-T	Input	Blood meal	300	g	Blood meal, spray dried, consumption mix, at feed compound plant/NL Mass	Agri-footprint	Production from cows, pigs and chicken (spray dried), mass allocation: 18% Trophic Level = 2.21 (Bonhommeau et al., 2013; Duarte et al., 2009)	(El‐Sayed, 1998)
		Wheat bran	460	g	Wheat bran, from wet milling, at plant/UK Mass	Agri-footprint	By-product of wheat grain milling and grinding mass allocation: 11.96%	
		Corn starch	100	g	Maize starch {RoW}| production | APOS, U	Ecoinvent 3	0.465 g C/g ingredient	
		Sardine oil	15	g	Fish oil, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 2% (M. R. Hasan & Halwart, 2009; Ytrestøyl et al., 2015)	

							Trophic Level = 2.4 (Menhaden)	
		Soybean oil	15	g	Soybean oil, crude GLO | market for | APOS, U	Ecoinvent 3	Yield = 18.33% (Irwin, 2017) 2.88 g C / g ingredient	
		Vitamin mix	10	g	Ascorbic acid {RoW}| ascorbic acid production | APOS, U	Ecoinvent 3	Vitamins have zero external biotic resource use	
		Mineral mix	10	g	Iron(III) sulfate, without water, in 12.5% iron solution state {CA-QC}| production | APOS, U	Ecoinvent 3	Trace mineral 12.5% solution, zero external biotic resource use	
		Monocalcium phosphate	20	g	Triple superphosphate, as 80% Ca(H2PO4)2 (NPK 0-48-0), at plant/RER Mass	Agri-footprint	Micro minerals have zero external biotic resource use	
		Alpha cellulose	70	g	Cellulose fibre, inclusive blowing in GLO | market for | APOS, U	Ecoinvent 3	0.444 g C / g ingredient	

Table B26. Diet formulation inventory for FMF-3-P.

	Section	Material	Amount	Unit	Corresponding LCI	Database	Assumptions / Comments	Reference
1 kg FMF-3-P	Input	Corn gluten meal (CGM)	360	g	Maize gluten meal, from wet milling (gluten drying), at plant/US Mass	Agri-footprint	0.528 g C / g ingredient	(Adelizi et al., 1998)
		Yellow corn	152	g	Corn grain, at conversion plant, 2022/ton/RNA	USLCI	CDDGS (corn dried distilled grains with solubles) 0.465 g C / g ingredient	
		Corn gluten feed	125	g	Maize gluten feed, from wet milling (glutenfeed production, with drying), at plant/US Mass	Agri-footprint	Maize wet milling process Yield = 21% (Hoffman, 1990) 2.232 g C /g ingredient	
		Peanut meal	204	g	Peanut {RoW}| peanut production | APOS, U	Ecoinvent 3	0.774 g C / g ingredient	

		Soybean oil	7	g	Soybean oil, crude GLO | market for | APOS, U	Ecoinvent 3	Yield = 18.33% (Irwin, 2017) 2.88 g C / g ingredient	
		Menhadden oil	95	g	Fish oil, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 2% (M. R. Hasan & Halwart, 2009; Ytrestøyl et al., 2015) Trophic Level = 2.4 (Menhaden)	
		Lysine	10.2	g	Glycine {RoW}| market for | APOS, U	Ecoinvent 3	Additional amino acids have zero external biotic resource use	
		Methionine	1.7	g				
		Dicalcium phosphate	32.7	g	Triple superphosphate, as 80% Ca(H2PO4)2 (NPK 0-48-0), at plant/RER Mass	Agri-footprint	Micro minerals have zero external biotic resource use	
		Vitamin premix	3	g	Ascorbic acid {RoW}| ascorbic acid production | APOS, U	Ecoinvent 3	Vitamins have zero external biotic resource use	
		Mineral premix	1.5	g	Iron(III) sulfate, without water, in 12.5% iron solution state {CA-QC}| production | APOS, U	Ecoinvent 3	Trace mineral 12.5% solution zero external biotic resource use	
		Vitamin C	1	g	Ascorbic acid {RoW}| ascorbic acid production | APOS, U	Ecoinvent 3	Vitamins have zero external biotic resource use	
		Choline Cl	7	g	Glycine {RoW}| market for | APOS, U	Ecoinvent 3	Additional amino acids have zero external biotic resource use	

Table B27. Diet formulation inventory for FMF-4-P.

	Section	Material	Amount	Unit	Corresponding LCI	Database	Assumptions / Comments	Reference
1 kg FMF-3-P	Input	Corn gluten meal (CGM)	227	g	Maize gluten meal, from wet milling (gluten drying), at plant/US Mass	Agri-footprint	0.528 g C / g ingredient	(Adelizi et al., 1998)

		Yellow corn	184	g	Corn grain, at conversion plant, 2022/ton/RNA	USLCI	CDDGS (corn dried distilled grains with solubles) 0.465 g C / g ingredient	
		Corn gluten feed	32	g	Maize gluten feed, from wet milling (glutenfeed production, with drying), at plant/US Mass	Agri-footprint	Maize wet milling process Yield = 21% (Hoffman, 1990) 2.232 g C /g ingredient	
		Soybean meal	403	g	Soybean meal {US}| soybean meal and crude oil production | APOS, U	Ecoinvent 3	0.528 g C / g ingredient	
		Soybean oil	7	g	Soybean oil, crude GLO | market for | APOS, U	Ecoinvent 3	Yield = 18.33% (Irwin, 2017) 2.88 g C / g ingredient	
		Menhadden oil	95	g	Fish oil, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 2% (Ytrestøyl et al., 2015) Trophic Level = 2.4 (Menhaden)	
		Lysine	1.3	g	Glycine {RoW}| market for | APOS, U	Ecoinvent 3	Additional amino acids have zero external biotic resource use	
		Methionine	2.4	g				
		Dicalcium phosphate	35.6	g	Triple superphosphate, as 80% Ca(H2PO4)2 (NPK 0-48-0), at plant/RER Mass	Agri-footprint	Micro minerals have zero external biotic resource use	
		Vitamin premix	3	g	Ascorbic acid {RoW}| ascorbic acid production | APOS, U	Ecoinvent 3	Vitamins have zero external biotic resource use	
		Mineral premix	1.5	g	Iron(III) sulfate, without water, in 12.5% iron solution state {CA-QC}| production | APOS, U	Ecoinvent 3	Trace mineral 12.5% solution zero external biotic resource use	
		Vitamin C	1	g	Ascorbic acid {RoW}| ascorbic acid production | APOS, U	Ecoinvent 3	Vitamins have zero external biotic resource use	

		Choline Cl	7	g	Glycine {RoW}| market for | APOS, U	Ecoinvent 3	Additional amino acids have zero external biotic resource use	

Table B28. Diet formulation inventory for FMF-5-S.

	Section	Material	Amount	Unit	Corresponding LCI	Database	Assumptions / Comments	Reference
1 kg FMF-5-S	Input	Alaskan pollock fish meal	152.95	g	Fish meal, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Fish meal by-products mass allocation: 35% (Aas et al., 2019)	(Ian Forster et al., 2004)
		Menhaden oil	29	g	Fish oil, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 2% (M. R. Hasan & Halwart, 2009; Ytrestøyl et al., 2015) Trophic Level = 2.4 (Menhaden)	
		Wheat starch	13.85	g	Wheat starch slurry, from wet milling, at plant/UK Mass	Agri-footprint	0.460 g C / g ingredient	
		Whole wheat flour	555	g	Wheat flour, from dry milling, at plant/UK Mass	Agri-footprint		
		Vital wheat gluten	40	g	Wheat gluten feed, from wet milling, at plant/UK Mass	Agri-footprint	14% gluten content, 3.286 g C / g ingredient	
		Brewer's yeast	50	g	Protein feed, 100% crude GLO| fodder yeast to generic market for protein feed | APOS, U	Ecoinvent 3	Yeast has zero external biotic resource use	
		Squid liver powder	25	g	N/S*	N/S*	N/S*	

		Soybean meal	90	g	Soybean meal {US}| soybean meal and crude oil production | APOS, U	Ecoinvent 3	0.528 g C / g ingredient	
		Soy lecithin	20	g	Soybean lecithin, from crushing (solvent), at plant/UK Mass	Agri-footprint	56% oil extraction yield, 0.942 g C / g ingredient	
		Cholesterol	2.4	g	Fatty acid GLO | market for | APOS, U	Ecoinvent 3	Cholesterol has zero external biotic resource use	
		Vitamin premix	4	g	Ascorbic acid {RoW}| ascorbic acid production | APOS, U	Ecoinvent 3	Vitamins have zero external biotic resource use	
		Choline Cl	1.2	g	Glycine {RoW}| market for | APOS, U	Ecoinvent 3	Additional amino acids have zero external biotic resource use	
		Vitamin C	0.8	g	Ascorbic acid {RoW}| ascorbic acid production | APOS, U	Ecoinvent 3	Vitamins have zero external biotic resource use	
		Phosphate minerals (as Sodium)	16.8	g	Sodium phosphate GLO | market for | APOS, U	Ecoinvent 3	Micro minerals have zero external biotic resource use	

* N/S: Not Specified

Table B29. Diet formulation inventory for FOF-1.

	Section	Material	Amount	Unit	Corresponding LCI	Database	Assumptions / Comments	Reference
1 kg FOF-1	Input	Fish meal	250	g	Fish meal, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 0.22 (Barlow, 2003) Trophic Level = 2.4 (Menhaden)	(Carter et al., 2003)
		Soybean meal	56.2	g	Soybean meal {US}| soybean meal and crude oil production | APOS, U	Ecoinvent 3	0.528 g C/g ingredient	
		Casein	143.2	g	Protein feed, 100% crude GLO | skimmed milk, from cow milk to generic	Ecoinvent 3	Zero external biotic resource use Concentrated protein from	

					market for protein feed | APOS, U		skimmed milk (butter production)	
		Wheat Gluten	100	g	Wheat gluten feed, from wet milling, at plant/UK Mass	Agri-footprint	14% gluten content 3.286 g C/g ingredient	
		Canola oil	169.6	g	Rape oil, crude {RoW}| rape oil mill operation | APOS, U	Ecoinvent 3	60% contented oil extraction yield (Citeau et al., 2018) 1.012 g C/g ingredient	
		Fish oil	0	g	Fish oil, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 2% (Ytrestøyl et al., 2015) Trophic Level = 2.4 (Menhaden)	
		Thraustochytrid meal	0	g	Created (Table S3)	N/A*	N/A*	
		Pregelatinized starch	150	g	Wheat starch slurry, from wet milling, at plant/UK Mass	Agri-footprint	0.46 g C / g ingredient	
		Vitamin mix	3	g	Ascorbic acid {RoW}| ascorbic acid production | APOS, U	Ecoinvent 3	Zero external biotic resource use	
		Stay C	3	g				
		Choline CL	2	g	Glycine {RoW}| market for | APOS, U	Ecoinvent 3	Zero external biotic resource use	
		Mineral mix	5	g	Iron(III) sulfate, without water, in 12.5% iron solution state {CA-QC}| production | APOS, U	Ecoinvent 3	12.5% solution, Trace minerals, zero external biotic resource use	
		Calsium phosphate	21.8	g	Triple superphosphate, as 80% Ca(H2PO4)2 (NPK 0-48-0), at plant/RER Mass	Agri-footprint	Zero external biotic resource use	
		Cellulose	36.2	g	Cellulose fibre, inclusive blowing in (Tchobanoglous et al.)| market for | APOS, U	Ecoinvent 3	0.444 g C / g ingredient	

		Bentonite	49	g	Iron(III) sulfate, without water, in 12.5% iron solution state {CA-QC}| production | APOS, U	Ecoinvent 3	Trace mineral, 12.5% solution, zero external biotic resource use	
		CMC (Carboxymethyl Cellulose)	9	g	Carboxymethyl cellulose, powder (Tchobanoglous et al.)| market for | APOS, U	Ecoinvent 3	0.399 g C / g ingredient	
		Cholestane	1	g	Fatty acid (Tchobanoglous et al.)| market for | APOS, U	Ecoinvent 3	Zero external biotic resource use	
		Yttrium oxide	1	g	Iron(III) sulfate, without water, in 12.5% iron solution state {CA-QC}| production | APOS, U	Ecoinvent 3	Trace mineral, 12.5% solution, zero external biotic resource use	

* N/A: Not Applicable

Table B30. Diet formulation inventory for FOF-2.

	Section	Material	Amount	Unit	Corresponding LCI	Database	Assumptions / Comments	Reference
1 kg FOF-2	Input	Fish meal	250	g	Fish meal, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 0.22 (Barlow, 2003) Trophic Level = 2.4 (Menhaden)	(Carter et al., 2003)
		Soybean meal	36.5	g	Soybean meal {US}| soybean meal and crude oil production | APOS, U	Ecoinvent 3	0.528 g C/g ingredient	
		Casein	132.9	g	Protein feed, 100% crude GLO | skimmed milk, from cow milk to generic market for protein feed | APOS, U	Ecoinvent 3	Zero external biotic resource use Concentrated protein from skimmed milk (butter production)	
		Wheat Gluten	100	g	Wheat gluten feed, from wet milling, at plant/UK Mass	Agri-footprint	14% gluten content 3.286 g C/g ingredient	

		Canola oil	110.5	g	Rape oil, crude {RoW}| rape oil mill operation | APOS, U	Ecoinvent 3	60% contented oil extraction yield (Citeau et al., 2018) 1.012 g C/g ingredient	
		Fish oil	0	g	Fish oil, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 2% (M. R. Hasan & Halwart, 2009; Ytrestøyl et al., 2015) Trophic Level = 2.4 (Menhaden)	
		Thraustochytrid meal	100	g	Created (Table S3)	N/A*	N/A*	
		Pregelatinized starch	150	g	Wheat starch slurry, from wet milling, at plant/UK Mass	Agri-footprint	0.46 g C / g ingredient	
		Vitamin mix	3	g	Ascorbic acid {RoW}| ascorbic acid production | APOS, U	Ecoinvent 3	Zero external biotic resource use	
		Stay C	3	g				
		Choline CL	2	g	Glycine {RoW}| market for | APOS, U	Ecoinvent 3	Zero external biotic resource use	
		Mineral mix	5	g	Iron(III) sulfate, without water, in 12.5% iron solution state {CA-QC}| production | APOS, U	Ecoinvent 3	12.5% solution, Trace minerals, zero external biotic resource use	
		Calsium phosphate	23	g	Triple superphosphate, as 80% Ca(H2PO4)2 (NPK 0-48-0), at plant/RER Mass	Agri-footprint	Micro minerals, zero external biotic resource use	
		Cellulose	24.2	g	Cellulose fibre, inclusive blowing in (Tchobanoglous et al.)| market for | APOS, U	Ecoinvent 3	0.444 g C / g ingredient	
		Bentonite	49	g	Iron(III) sulfate, without water, in 12.5% iron solution state {CA-QC}| production | APOS, U	Ecoinvent 3	Trace mineral, 12.5% solution, zero external biotic resource use	

		CMC (Carboxymethyl Cellulose)	9	g	Carboxymethyl cellulose, powder (Tchobanoglous et al.)| market for | APOS, U	Ecoinvent 3	0.399 g C / g ingredient	
		Cholestane	1	g	Fatty acid (Tchobanoglous et al.)| market for | APOS, U	Ecoinvent 3	Zero external biotic resource use	
		Yttrium oxide	1	g	Iron(III) sulfate, without water, in 12.5% iron solution state {CA-QC}| production | APOS, U	Ecoinvent 3	Trace mineral, 12.5% solution, zero external biotic resource use	

* N/A: Not Applicable

Table B31. Diet formulation inventory for FMOF.

	Section	Material	Amount	Unit	Corresponding LCI	Database	Assumptions / Comments	Reference
1 kg FMOF	Input	Mixed Nut Meal	320	g	Groundnut meal, from crushing, at plant/US Mass	Agri-footprint	0.752 g C / g ingredient	(John Davidson et al., 2016)
		Poultry Meal	295	g	Chicken co-product, other, at slaughterhouse/NL Mass	Agri-footprint	Chicken meat production co-product mass allocation: 13.76% Trophic Level = 2.21 (Duarte et al., 2009, Bonhommeau et al., 2013)	
		Wheat Flour	99.4	g	Wheat flour, from dry milling, at plant/UK Mass	Agri-footprint	0.46 g C/g ingredient	
		Menhaden Meal	0	g	Fish meal, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 0.22 (Davis, 2015) Trophic Level = 2.4 (Menhaden)	
		Fish Oil (whitefish Trimming oil)	182	g	Fish oil, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Fish oil by-products mass allocation: 35% (Aas et al., 2019)	
		Fish Oil (menhaden)	0	g	Fish oil, from fish meal and oil production, at plant/UK Mass	Agri-footprint	Yield = 2% (M. R. Hasan & Halwart, 2009; Ytrestøyl et al., 2015)	

							Trophic Level = 2.4 (Menhaden)	
		Soy Protein Concentrate	0	g	Soy protein concentrate, consumption mix, at feed compound plant/NL Mass	Agri-footprint	Yield = 0.75% (Erickson, 2015)	
		Blood Meal	0	g	Blood meal, spray dried, consumpton mix, at feed compound plant/NL Mass	Agri-footprint	Production from cows, pigs and chicken (spray dried), mass allocation: 18% Trophic Level = 2.21 (Duarte et al., 2009, Bonhommeau et al., 2013)	
		Canola Oil	0	g	Rape oil, crude {RoW}| rape oil mill operation | APOS, U	Ecoinvent 3	60% contented oil extraction yield (Citeau et al., 2018)	
		Corn Protein Concentrate	35.6	g	Protein feed, 100% crude {RoW}| maize grain to generic market for energy feed | APOS, U	Ecoinvent 3	Yield = 0.75% (Erickson, 2015)	
		Dicalcium phosphate	32.5	g	Triple superphosphate, as 80% Ca(H2PO4)2 (NPK 0-48-0), at plant/RER Mass	Agri-footprint	Micro minerals, zero external biotic resource use	
		Vitamin Premixg	10	g	Ascorbic acid {RoW}s| ascorbic acid production | APOS, U	Ecoinvent 3	Zero external biotic resource use	
		Lysine-HCL	6.2	g	Glycine {RoW}| market for | APOS, U	Ecoinvent 3	Additional amino acids, Zero external biotic resource use	
		Choline CL	6	g				
		Taurine	5	g				
		DL-Methionine	2.8	g				
		Stay-C	3	g	Ascorbic acid {RoW}| ascorbic acid production | APOS, U	Ecoinvent 3	Zero external biotic resource use	

		Threonine	0.5	g	Glycine {RoW}| market for | APOS, U	Ecoinvent 3	Additional amino acids, Zero external biotic resource use	
		Trace Minerals Premix	1	g	Iron(III) sulfate, without water, in 12.5% iron solution state {CA-QC}| production | APOS, U	Ecoinvent 3	12.5% solution, Trace minerals, zero external biotic resource use	
		Astaxanthin (Dye)	1	g	Dinitroaniline-compound {RoW}| production | APOS, U	Ecoinvent 3	Food coloring, zero external biotic resource use	

Table B32. Quantification of environmental impacts based on unit mass of aquafeed, protein, and live-weight seafood.

Environmental impacts quantities of aquafeeds based on unit mass (1 kg) feed production.												
Impact	OD	GW	PS	AC	EU	HHC	HHNC	RE	EC	FF	WI	BRU
Unit	kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	CTUh	CTUh	kg PM2.5 eq	CTUe	MJ surplus	Liters	g C
FMOC-1	1.02286E-07	4.39584155	0.163556273	0.033498411	0.020592823	5.43667E-08	2.93268E-06	0.001531245	19.40653708	2.73101349	21.90384675	84354.268
FMOC-2	6.61326E-08	1.068929697	0.099047011	0.007941456	0.007100867	3.30195E-08	8.16365E-07	0.000717412	5.99131443	1.291492349	25.1	49359.905
FMOC-3	4.06051E-08	3.595176114	0.112081593	0.00965031	0.010243392	3.70445E-08	1.25434E-06	0.000529027	64.82399249	1.85764652	46.7405349	10759.19276
FMOC-4	1.51624E-07	2.816482544	0.136586433	0.012481828	0.016085706	6.50338E-08	2.18346E-06	0.001201871	12.92339018	2.014105229	42.37496091	46068.55935
FMF-1-T	4.67573E-08	1.492649034	0.058573554	0.0117707	0.008060428	2.67146E-08	1.02468E-06	0.000665747	7.935166247	0.910715891	12.40977861	28150.59457
FMF-2-T	1.35185E-07	8.198527786	0.191028742	0.080871367	0.04671108	9.89843E-08	6.80838E-06	0.003232137	42.25221949	4.524945149	65.23256072	10679.08736
FMF-3-P	6.4435E-08	1.247422934	0.102148312	0.013225238	0.012699096	5.55783E-08	1.59183E-06	0.000800189	7.596648347	1.42018167	63.04585011	48227.23334
FMF-4-P	4.00908E-08	0.675773508	0.063472936	0.005812385	0.00469351	1.82272E-08	8.90553E-07	0.00043331	4.164635572	0.867914732	14.80033189	48085.95519
FMF-5-S	3.2069E-08	0.781235844	0.054817662	0.005964041	0.006898987	3.90121E-08	5.48266E-07	0.00040569	6.879622855	0.804583094	3.82	15649.42216

FOF-1	8.46435E-08	1.131145	0.093918	0.009997	0.011237	4.62E-08	1.52E-06	0.000839	7.182766	1.230828	30.49339	3569.823
FOF-2	9.29455E-08	10.92304259	0.652177618	0.093186463	0.01200567	7.27073E-08	1.64774E-06	0.005118449	13.09176819	9.787554772	-31.42687099	3494.2838
FMOF	8.66329E-08	2.937905	0.126713	0.023662	0.016728	4.7E-08	1.42E-06	0.001179	47.7724	2.139567	166.8458	36147.35
Environmental Impacts quantities of aquafeeds based on unit mass (1 kg) protein provision												
FMOC-1	2.42E-07	10.39206	0.386658	0.079192	0.048683	1.29E-07	6.93E-06	0.00362	45.87834	6.456297	51.78214	199419.0733
FMOC-2	1.61299E-07	2.607145602	0.241578075	0.019369406	0.017319189	8.05353E-08	1.99113E-06	0.001749784	14.61296202	3.149981339	61.2195122	120390.0122
FMOC-3	1.35E-07	11.94411	0.372364	0.032061	0.034031	1.23E-07	4.17E-06	0.001758	215.3621	6.171583	155.2842	35744.82646
FMOC-4	4.26E-07	7.911468	0.38367	0.035061	0.045185	1.83E-07	6.13E-06	0.003376	36.30166	5.657599	119.0308	129406.0656
FMF-1-T	1.21E-07	3.87701	0.152139	0.030573	0.020936	6.94E-08	2.66E-06	0.001729	20.61082	2.365496	32.23319	73118.42747
FMF-2-T	4.39E-07	26.6186	0.620223	0.262569	0.151659	3.21E-07	2.21E-05	0.010494	137.1825	14.69138	211.794	34672.36156
FMF-3-P	1.61E-07	3.126373	0.256011	0.033146	0.031827	1.39E-07	3.99E-06	0.002005	19.03922	3.559353	158.0096	120870.259
FMF-4-P	1.04E-07	1.755256	0.164865	0.015097	0.012191	4.73E-08	2.31E-06	0.001125	10.81724	2.254324	38.44242	124898.5849
FMF-5-S	9.43205E-08	2.297752483	0.161228417	0.017541298	0.020291138	1.14741E-07	1.61255E-06	0.001193204	20.23418487	2.366420866	11.23529412	46027.71224
FOF-1	2.12672E-07	2.842072924	0.235976046	0.025117102	0.028233277	1.15981E-07	3.80753E-06	0.002107998	18.04715113	3.092531582	76.6165502	8969.403518
FOF-2	2.38E-07	27.93617	1.667973	0.238329	0.030705	1.86E-07	4.21E-06	0.013091	33.48278	25.03211	-80.3756	8936.787212
FMOF	2.05291E-07	6.961859072	0.300268119	0.056071948	0.039639927	1.11355E-07	3.36286E-06	0.002793342	113.2047468	5.070065018	395.3691833	85657.23697
Environmental Impacts quantities of aquafeeds based on unit mass (1 kg) live-weight seafood production.												
FMOC-1	9.20571E-08	3.956257395	0.147200646	0.03014857	0.01853354	4.89301E-08	2.63941E-06	0.001378121	17.46588338	2.457912141	19.71346208	75918.8412
FMOC-2	5.6874E-08	0.919279539	0.085180429	0.006829653	0.006106746	2.83968E-08	7.02074E-07	0.000616974	5.15253041	1.11068342	21.586	42449.5183
FMOC-3	8.52707E-08	7.549869839	0.235371345	0.02026565	0.021511124	7.77935E-08	2.63411E-06	0.001110957	136.1303842	3.901057691	98.1551233	22594.3048

FMOC-4	1.83465E-07	3.407943878	0.165269584	0.015103012	0.019463704	7.86909E-08	2.64199E-06	0.001454264	15.63730212	2.437067327	51.2737027	55742.95682
FMF-1-T	1.16893E-07	3.731622584	0.146433884	0.02942675	0.020151071	6.67864E-08	2.56171E-06	0.001664366	19.83791562	2.276789727	31.02444653	70376.48644
FMF-2-T	3.51481E-07	21.31617224	0.49667473	0.210265555	0.121448808	2.57359E-07	1.77018E-05	0.008403556	109.8557707	11.76485739	169.6046579	27765.62714
FMF-3-P	7.79664E-08	1.50938175	0.123599457	0.016002538	0.015365906	6.72497E-08	1.92612E-06	0.000968229	9.1919445	1.718419821	76.28547863	58354.95234
FMF-4-P	5.01136E-08	0.844716885	0.07934117	0.007265482	0.005866888	2.2784E-08	1.11319E-06	0.000541638	5.205794465	1.084893415	18.50041486	60107.44399
FMF-5-S	4.26517E-08	1.039043673	0.07290749	0.007932175	0.009175653	5.1886E-08	7.29194E-07	0.000539567	9.149898397	1.070095516	5.0806	20813.73148
FOF-1	7.11005E-08	0.95016182	0.078891512	0.008397149	0.009438949	3.87747E-08	1.27293E-06	0.000704746	6.033523567	1.033895158	25.61444506	2998.650984
FOF-2	8.45804E-08	9.93996876	0.593481633	0.084799681	0.01092516	6.61636E-08	1.49945E-06	0.004657789	11.91350905	8.906674843	-28.5984526	3179.798258
FMOF	7.71033E-08	2.61473503	0.1127747	0.021059502	0.014887964	4.18227E-08	1.26302E-06	0.001049123	42.51743881	1.904215019	148.4927579	32171.14506

Table B33. Uncertainty analysis of FMOC-1 (based on 1 kg protein).

Impact category	Unit	Mean	Median	SD	CV	2.5%	97.5%	SEM
AC	kg SO2 eq	0.079134923	0.07912167	0.000460688	0.582154675	0.078267481	0.08004155	1.45682E-05
HHC	CTUh	1.28347E-07	1.2194E-07	2.96817E-08	23.12606808	1.10955E-07	1.88988E-07	9.38616E-10
EC	CTUe	45.7033971	45.20790041	1.860884129	4.071653854	43.66270675	50.41723343	0.058846323
EU	kg N eq	0.048575778	0.04846569	0.001187704	2.445054402	0.046635191	0.051063314	3.75585E-05
FF	MJ surplus	6.456443972	6.45279435	0.083583675	1.294577567	6.295184725	6.638765091	0.002643148
GW	kg CO2 eq	10.39305983	10.39279217	0.04282415	0.412045637	10.31226099	10.47666381	0.001354219
HHNC	CTUh	6.92195E-06	6.89373E-06	2.03833E-07	2.944739336	6.60662E-06	7.37594E-06	6.44578E-09
OD	kg CFC-11 eq	2.40752E-07	2.38045E-07	2.03707E-08	8.461272361	2.09718E-07	2.90269E-07	6.44177E-10
RE	kg PM2.5 eq	0.00360595	0.003602476	4.34466E-05	1.204859208	0.003530537	0.003701372	1.3739E-06
PS	kg O3 eq	0.387349813	0.387350338	0.005317287	1.372735055	0.377099297	0.397981027	0.000168147
WI	liters	55.01907494	63.67477848	147.3125449	267.7481311	-261.4760112	314.8216319	4.658431698

* Monte Carlo Criterion: fixed number of runs = 1000, Confidence Interval = 95%.

Table B34. Uncertainty analysis of 1 kg FMOC-2 (based on 1 kg protein).

Impact category	Unit	Mean	Median	SD	CV	2.5%	97.5%	SEM
AC	kg SO2 eq	0.019366718	0.019350672	0.000626143	3.233085522	0.018173083	0.020698269	1.98004E-05
HHC	CTUh	7.91564E-08	7.29778E-08	3.13541E-08	39.61040078	5.46407E-08	1.40495E-07	9.91505E-10
EC	CTUe	14.369913	13.35984008	3.888574104	27.06052641	10.69171829	25.14642862	0.12296751
EU	kg N eq	0.017298576	0.017192729	0.001556269	8.996516825	0.014705135	0.020691047	4.92136E-05
FF	MJ surplus	3.149225769	3.14427877	0.070387996	2.235088922	3.02320199	3.287116162	0.002225864
GW	kg CO2 eq	2.607263959	2.60798418	0.059023564	2.263812355	2.496410965	2.722151667	0.001866489
HHNC	CTUh	1.98538E-06	1.93693E-06	5.4994E-07	27.69942047	1.48579E-06	2.70138E-06	1.73906E-08
OD	kg CFC-11 eq	1.60005E-07	1.56663E-07	2.52497E-08	15.78060441	1.27366E-07	2.20712E-07	7.98466E-10
RE	kg PM2.5 eq	0.001748634	0.00174642	5.81864E-05	3.327536394	0.001639597	0.001875654	1.84002E-06
PS	kg O3 eq	0.241476333	0.241237066	0.003888314	1.610225827	0.23421493	0.249400677	0.000122959
WI	liters	71.06150658	79.47632741	177.5573864	249.8643709	-259.7928465	396.5570959	5.614857563

* Monte Carlo Criterion: fixed number of runs = 1000, Confidence Interval = 95%.

Table B35. Uncertainty analysis of 1 kg FMOC-3 (based on 1 kg protein).

Impact category	Unit	Mean	Median	SD	CV	2.5%	97.5%	SEM
AC	kg SO2 eq	0.032042277	0.032022682	0.000306602	0.956865969	0.031490866	0.032697781	9.6956E-06
HHC	CTUh	1.23964E-07	1.18202E-07	2.91519E-08	23.51638876	1.10806E-07	1.67476E-07	9.21863E-10
EC	CTUe	215.2907702	214.9719681	1.416084626	0.657754452	213.7874611	219.156292	0.044780528
EU	kg N eq	0.034005836	0.033938503	0.000581689	1.710555448	0.033165889	0.03527323	1.83946E-05
FF	MJ surplus	6.124186408	6.121258661	0.135920082	2.219398188	5.876926368	6.408260211	0.00429817
GW	kg CO2 eq	11.93053716	11.92965438	0.046805808	0.392319367	11.84689993	12.02385161	0.00148013
HHNC	CTUh	4.16463E-06	4.14324E-06	1.16761E-07	2.803623253	4.07055E-06	4.37687E-06	3.69229E-09
OD	kg CFC-11 eq	1.34193E-07	1.33398E-07	6.14827E-09	4.581670953	1.24268E-07	1.49367E-07	1.94425E-10
RE	kg PM2.5 eq	0.001750443	0.001747065	2.81497E-05	1.60814857	0.001703384	0.001813846	8.90173E-07
PS	kg O3 eq	0.372527486	0.372246546	0.007012792	1.882489939	0.359471477	0.387805632	0.000221764
WI	liters	163.7018309	168.4640388	110.6762974	67.60846646	-78.46360677	364.3076373	3.499891829

* Monte Carlo Criterion: fixed number of runs = 1000, Confidence Interval = 95%.

Table B36. Uncertainty analysis of 1 kg FMOC-4 (based on 1 kg protein).

Impact category	Unit	Mean	Median	SD	CV	2.5%	97.5%	SEM
AC	kg SO2 eq	0.035019478	0.034882292	0.001676472	4.787255384	0.031958275	0.038533818	5.30147E-05
HHC	CTUh	1.84637E-07	1.70703E-07	1.04716E-07	56.71487646	1.30997E-07	3.30802E-07	3.31142E-09
EC	CTUe	36.43390701	35.32556405	5.03863686	13.8295266	30.64652336	49.45830425	0.159335688
EU	kg N eq	0.045033863	0.044808167	0.00409417	9.091314992	0.037638601	0.053926153	0.000129469
FF	MJ surplus	5.658055991	5.640245766	0.226079375	3.995707638	5.260714109	6.127127487	0.007149258
GW	kg CO2 eq	7.910203225	7.897559346	0.160599218	2.030279293	7.609443949	8.276477895	0.005078593
HHNC	CTUh	6.09855E-06	6.02593E-06	7.08662E-07	11.62018198	4.876E-06	7.6541E-06	2.24099E-08
OD	kg CFC-11 eq	4.26039E-07	4.1718E-07	6.78118E-08	15.91680118	3.29294E-07	5.71133E-07	2.1444E-09
RE	kg PM2.5 eq	0.003377031	0.003369082	0.00015133	4.48115945	0.003102386	0.003709251	4.78548E-06
PS	kg O3 eq	0.383917253	0.383540958	0.010209161	2.659208732	0.365233502	0.404440462	0.000322842
WI	liters	106.4632682	124.2693606	410.7123922	385.7784936	-736.7783437	853.7018358	12.98786623

* Monte Carlo Criterion: fixed number of runs = 1000, Confidence Interval = 95%.

Table B37. Uncertainty analysis of 1 kg FMF-1-T (based on 1 kg protein).

Impact category	Unit	Mean	Median	SD	CV	2.5%	97.5%	SEM
AC	kg SO2 eq	0.030277836	0.030256526	0.000290404	0.959129574	0.029782369	0.030915988	9.18337E-06
HHC	CTUh	6.80928E-08	6.11708E-08	3.98197E-08	58.47861698	5.0513E-08	1.18364E-07	1.25921E-09
EC	CTUe	20.10080496	19.69338426	1.700469974	8.459710829	18.2082663	24.62489145	0.053773582
EU	kg N eq	0.020829094	0.020708822	0.000817528	3.924931261	0.019570209	0.022799395	2.58525E-05
FF	MJ surplus	2.320436753	2.315061456	0.059976708	2.584716362	2.217204964	2.450632434	0.00189663
GW	kg CO2 eq	3.863320005	3.8593927	0.04817733	1.24704478	3.780924888	3.968828465	0.001523501
HHNC	CTUh	2.63569E-06	2.61614E-06	1.12592E-07	4.271833076	2.49562E-06	2.90703E-06	3.56048E-09
OD	kg CFC-11 eq	1.18719E-07	1.16563E-07	1.38014E-08	11.62527748	9.92859E-08	1.52271E-07	4.36438E-10
RE	kg PM2.5 eq	0.001685484	0.001679433	4.63021E-05	2.747111716	0.00161358	0.001794548	1.4642E-06
PS	kg O3 eq	0.150434882	0.15012802	0.004208926	2.79783919	0.143027489	0.15942468	0.000133098
WI	liters	29.10947258	35.75910134	108.2883848	372.0039394	-200.8548064	218.8185602	3.4243794

* Monte Carlo Criterion: fixed number of runs = 1000, Confidence Interval = 95%.

Table B38. Uncertainty analysis of 1 kg FMF-2-T (based on 1 kg protein).

Impact category	Unit	Mean	Median	SD	CV	2.5%	97.5%	SEM
AC	kg SO2 eq	0.261168534	0.261173565	0.000838121	0.320911866	0.259536191	0.262821217	2.65037E-05
HHC	CTUh	3.14657E-07	3.06499E-07	3.67157E-08	11.66846901	2.89013E-07	4.02966E-07	1.16105E-09
EC	CTUe	135.7373593	134.5555028	4.568075095	3.365377902	131.3763347	149.1292854	0.144455218
EU	kg N eq	0.151422657	0.151231555	0.001599341	1.056209872	0.149078971	0.154779472	5.05756E-05
FF	MJ surplus	14.51925246	14.51246656	0.19680321	1.355463796	14.14225833	14.92004047	0.006223464
GW	kg CO2 eq	26.79817828	26.79616356	0.118417201	0.441885265	26.57727205	27.0244746	0.003744681
HHNC	CTUh	2.18609E-05	2.17966E-05	3.41523E-07	1.562252994	2.15369E-05	2.2497E-05	1.07999E-08
OD	kg CFC-11 eq	4.28103E-07	4.26909E-07	1.74545E-08	4.077175088	3.98794E-07	4.69508E-07	5.51959E-10
RE	kg PM2.5 eq	0.010524714	0.010520816	6.99174E-05	0.664316003	0.01040107	0.010677023	2.21098E-06
PS	kg O3 eq	0.620080072	0.61943385	0.01487257	2.39849187	0.592094443	0.650202325	0.000470312
WI	liters	197.4434886	206.7230393	167.8124792	84.9926632	-177.2655424	512.1010583	5.306696542

* Monte Carlo Criterion: fixed number of runs = 1000, Confidence Interval = 95%.

Table B39. Uncertainty analysis of 1 kg FMF-3-P (based on 1 kg protein).

Impact category	Unit	Mean	Median	SD	CV	2.5%	97.5%	SEM
AC	kg SO2 eq	0.03290542	0.032729012	0.001640067	4.984183913	0.030192189	0.036466887	5.18635E-05
HHC	CTUh	1.36498E-07	1.30474E-07	3.10012E-08	22.71179536	9.84128E-08	2.06316E-07	9.80345E-10
EC	CTUe	19.03587165	18.37147271	2.557640308	13.43589806	16.12783513	26.62296545	0.080879688
EU	kg N eq	0.031987003	0.031405436	0.003463341	10.82733799	0.026576354	0.040518828	0.00010952
FF	MJ surplus	3.502776698	3.498483723	0.143149832	4.08675301	3.236370893	3.787845056	0.004526795
GW	kg CO2 eq	3.20785718	3.203714931	0.159000992	4.956610678	2.891532722	3.536696968	0.005028053
HHNC	CTUh	3.93298E-06	3.89922E-06	1.40115E-07	3.562557128	3.78836E-06	4.33431E-06	4.43081E-09
OD	kg CFC-11 eq	1.59974E-07	1.55455E-07	2.72023E-08	17.00423148	1.19901E-07	2.34968E-07	8.60212E-10
RE	kg PM2.5 eq	0.002064397	0.002056641	9.97547E-05	4.832148876	0.001885582	0.002269152	3.15452E-06
PS	kg O3 eq	0.256273968	0.255585938	0.011193798	4.36790302	0.236355038	0.280363402	0.000353979
WI	liters	159.0783286	165.4835153	163.6751017	102.8896287	-211.5816023	469.5302765	5.175861175

* Monte Carlo Criterion: fixed number of runs = 1000, Confidence Interval = 95%.

Table B40. Uncertainty analysis of 1 kg FMF-4-P (based on 1 kg protein).

Impact category	Unit	Mean	Median	SD	CV	2.5%	97.5%	SEM
AC	kg SO2 eq	0.014875213	0.014873682	0.000231751	1.557969486	0.014460926	0.015380118	7.32862E-06

HHC	CTUh	4.53565E-08	4.12574E-08	1.84348E-08	40.644155	3.3085E-08	8.307E-08	5.82958E-10
EC	CTUe	10.7829059	10.4874421	1.198549436	11.11527307	9.346989531	13.76098802	0.037901461
EU	kg N eq	0.012263133	0.012141808	0.000589015	4.803133833	0.011520008	0.013776067	1.86263E-05
FF	MJ surplus	2.191878025	2.188471104	0.071902899	3.280424274	2.067804355	2.351219858	0.002273769
GW	kg CO2 eq	1.826381436	1.823577818	0.046154425	2.527096677	1.742592135	1.924906259	0.001459531
HHNC	CTUh	2.26385E-06	2.23825E-06	2.46409E-07	10.88449401	2.19163E-06	2.42938E-06	7.79213E-09
OD	kg CFC-11 eq	1.03347E-07	1.00067E-07	1.72447E-08	16.68620243	7.98124E-08	1.41846E-07	5.45326E-10
RE	kg PM2.5 eq	0.001188624	0.001185169	4.06585E-05	3.420636923	0.001124701	0.001284452	1.28573E-06
PS	kg O3 eq	0.165191	0.165109829	0.005030262	3.045118628	0.155942129	0.175455406	0.000159071
WI	liters	42.31870405	52.91643132	92.86504529	219.4420821	-167.6837956	203.0498436	2.936650581

* Monte Carlo Criterion: fixed number of runs = 1000, Confidence Interval = 95%.

Table B41. Uncertainty analysis of 1 kg FMF-5-S (based on 1 kg protein).

Impact category	Unit	Mean	Median	SD	CV	2.5%	97.5%	SEM
AC	kg SO2 eq	0.017548049	0.017529669	0.000203915	1.162038038	0.017200319	0.017986701	6.44836E-06
HHC	CTUh	1.16316E-07	1.00176E-07	5.62033E-08	48.31949904	5.60604E-08	2.80126E-07	1.7773E-09
EC	CTUe	20.19493622	19.7419406	2.239024563	11.08705934	17.49576865	25.76882056	0.070804174
EU	kg N eq	0.020287813	0.020148889	0.00067765	3.340183674	0.019445717	0.022080563	2.14292E-05
FF	MJ surplus	2.369739462	2.368068335	0.042649382	1.799749822	2.291640912	2.457699019	0.001348692
GW	kg CO2 eq	2.29918055	2.298051285	0.024100542	1.048223103	2.256915612	2.350506569	0.000762126
HHNC	CTUh	1.60745E-06	1.58117E-06	1.13036E-07	7.032027922	1.51572E-06	1.87071E-06	3.57453E-09
OD	kg CFC-11 eq	9.47644E-08	9.28938E-08	1.07393E-08	11.33259141	7.95594E-08	1.21063E-07	3.39605E-10
RE	kg PM2.5 eq	0.001193201	0.001190621	3.14816E-05	2.638418048	0.001138078	0.001262614	9.95536E-07
PS	kg O3 eq	0.161377125	0.161217778	0.001735078	1.075169992	0.15826855	0.16512567	5.4868E-05
WI	liters	7.12015251	13.17285952	83.29106343	1169.79325	-176.5956624	157.4996649	2.633894692

* Monte Carlo Criterion: fixed number of runs = 1000, Confidence Interval = 95%.

Table B42. Uncertainty analysis of 1 kg FOF-1 (based on 1 kg protein).

Impact category	Unit	Mean	Median	SD	CV	2.5%	97.5%	SEM
AC	kg SO2 eq	0.025177132	0.025140773	0.001324082	5.259064967	0.022881959	0.028023473	4.18711E-05
HHC	CTUh	1.14251E-07	1.08164E-07	3.22045E-08	28.18739059	8.2844E-08	1.89699E-07	1.0184E-09
EC	CTUe	18.141869	16.89877299	4.961464759	27.34814565	13.47253915	30.01513035	0.156895292

EU	kg N eq	0.028345081	0.028003733	0.003026817	10.67845478	0.023177515	0.035217014	9.57163E-05
FF	MJ surplus	3.098876286	3.095324369	0.111942434	3.612355706	2.898906361	3.342230578	0.003539931
GW	kg CO2 eq	2.846098254	2.841820619	0.101660074	3.571910202	2.660463276	3.07215851	0.003214774
HHNC	CTUh	3.83578E-06	3.7522E-06	6.36491E-07	16.59353583	2.89828E-06	5.09861E-06	2.01276E-08
OD	kg CFC-11 eq	2.14736E-07	2.0792E-07	3.74952E-08	17.46103541	1.63583E-07	3.02822E-07	1.1857E-09
RE	kg PM2.5 eq	0.002111314	0.00210483	9.52008E-05	4.509077836	0.001950462	0.002321568	3.01051E-06
PS	kg O3 eq	0.23614026	0.23583148	0.007200868	3.049402989	0.223286126	0.251918075	0.000227711
WI	liters	77.21029543	99.5489689	267.2136103	346.0854654	-482.3601812	577.5254068	8.450036303

* Monte Carlo Criterion: fixed number of runs = 1000, Confidence Interval = 95%.

Table B43. Uncertainty analysis of 1 kg FOF-2 (based on 1 kg protein).

Impact category	Unit	Mean	Median	SD	CV	2.5%	97.5%	SEM
AC	kg SO2 eq	0.23832294	0.238311633	0.001101098	0.462019301	0.236187452	0.240633797	3.48198E-05
HHC	CTUh	1.84564E-07	1.72207E-07	5.2208E-08	28.28719714	1.38695E-07	3.30021E-07	1.65096E-09
EC	CTUe	33.37794022	31.6538299	7.128051548	21.35557647	27.03603836	50.47744351	0.225408782
EU	kg N eq	0.030650198	0.030462624	0.002976875	9.712416734	0.025774886	0.036501802	9.41371E-05
FF	MJ surplus	25.03119552	25.02413691	0.131483065	0.525276808	24.77555188	25.32708421	0.00415786
GW	kg CO2 eq	27.93470349	27.93083704	0.099581567	0.356479772	27.74863951	28.15045125	0.003149046
HHNC	CTUh	4.20075E-06	4.13657E-06	5.41568E-07	12.89218179	3.43689E-06	5.12989E-06	1.71259E-08
OD	kg CFC-11 eq	2.38841E-07	2.30745E-07	4.51142E-08	18.88879782	1.8177E-07	3.45036E-07	1.42664E-09
RE	kg PM2.5 eq	0.013088228	0.013080058	0.000112407	0.858842345	0.012891245	0.013342699	3.55463E-06
PS	kg O3 eq	1.667865133	1.667676582	0.006890819	0.413152067	1.655128032	1.682046734	0.000217907
WI	liters	-81.4560950	-70.11560089	356.2649104	-437.3704757	-850.6754801	581.8955339	11.26608567

* Monte Carlo Criterion: fixed number of runs = 1000, Confidence Interval = 95%.

Table B44. Uncertainty analysis of 1 kg FMOF (based on 1 kg protein).

Impact category	Unit	Mean	Median	SD	CV	2.5%	97.5%	SEM
AC	kg SO2 eq	0.056112497	0.056100943	0.000225003	0.40098548	0.055699421	0.056589249	7.11522E-06
HHC	CTUh	1.13641E-07	1.04858E-07	7.82473E-08	68.85489817	9.55054E-08	1.55482E-07	2.4744E-09
EC	CTUe	113.2278574	112.763531	1.904771789	1.682246608	111.2673714	117.8227624	0.060234173
EU	kg N eq	0.039611926	0.039481701	0.000595632	1.503667506	0.038801525	0.041371191	1.88355E-05
FF	MJ surplus	5.086660443	5.081161947	0.07982074	1.569216985	4.94961393	5.267998507	0.002524153

GW	kg CO2 eq	6.969819349	6.967553033	0.031709657	0.454956651	6.913955495	7.037992033	0.001002747
HHNC	CTUh	3.35792E-06	3.33692E-06	9.14804E-08	2.724314911	3.27553E-06	3.54978E-06	2.89286E-09
OD	kg CFC-11 eq	2.07131E-07	2.04443E-07	1.7673E-08	8.532294065	1.78357E-07	2.4918E-07	5.5887E-10
RE	kg PM2.5 eq	0.002796263	0.002793537	3.87038E-05	1.384127615	0.002729016	0.00288437	1.22392E-06
PS	kg O3 eq	0.301353386	0.301267772	0.003251553	1.078983556	0.295177298	0.308076016	0.000102823
WI	liters	393.1974904	399.7988176	126.9472067	32.28586391	105.583975	612.557713	4.014423156

* Monte Carlo Criterion: fixed number of runs = 1000, Confidence Interval = 95%.

Table B45. TRACI Environmental Impacts of blood meal based on unit mass (1 kg) meal production.

Impact category	**Unit**	**Total**	**Beef co-product, feed grade, from dairy cattle, at slaughterhouse/NL Mass**		**Chicken co-product, feed grade, at slaughterhouse/NL Mass**		**Pig co-product, feed grade, at slaughterhouse/NL Mass**		**Electricity mix, AC, consumption mix, at consumer, < 1kV NL S System - Copied from ELCD**		**Process steam from natural gas, heat plant, consumption mix, at plant, MJ NL S System - Copied from ELCD**	
OD	kg CFC-11 eq	2.99E-07	2.82E-08	9.42%	1.39E-07	46.31%	1.05E-07	35.01%	2.75E-08	9.19%	1.99E-10	0.07%
GW	kg CO2 eq	24.99936	3.531531	14.13%	11.92947	47.72%	8.481957	33.93%	0.446672	1.79%	0.609722	2.44%
PS	kg O3 eq	0.528571	0.057213	10.82%	0.244272	46.21%	0.21236	40.18%	0.007564	1.43%	0.007161	1.35%
AC	kg SO2 eq	0.251081	0.055395	22.06%	0.101426	40.40%	0.093328	37.17%	0.000583	0.23%	0.000349	0.14%
EU	kg N eq	0.133145	0.030996	23.28%	0.051188	38.45%	0.050914	38.24%	2.65E-05	0.02%	2.06E-05	0.02%
HHC	CTUh	2.48E-07	4.24E-08	17.12%	1.16E-07	46.82%	8.92E-08	36.00%	1.06E-10	0.04%	5.98E-11	0.02%
HHNC	CTUh	2.05E-05	5.87E-06	28.66%	6.91E-06	33.75%	7.7E-06	37.58%	3.19E-09	0.02%	3.26E-10	0.00%
RE	kg PM2.5 eq	0.009352	0.002012	21.51%	0.003809	40.73%	0.003487	37.28%	3.48E-05	0.37%	1.04E-05	0.11%
EC	CTUe	116.0076	10.79007	9.30%	53.01135	45.70%	52.19166	44.99%	0.008452	0.01%	0.00611	0.01%
FF	MJ surplus	12.11399	1.267562	10.46%	4.837161	39.93%	3.931652	32.46%	0.491254	4.06%	1.586359	13.10%

Table B46. TRACI Environmental Impacts corn gluten meal based on unit mass (1 kg) meal production.

Impact category	**Unit**	**Total**	**Corn grain, harvested and stored/kg/RNA**		**Transport, combination truck, diesel powered/US**		**Transport, train, diesel powered/US**		**Transport, barge, diesel powered/US**	
OD	kg CFC-11 eq	7.07322E-10	7.06902E-10	99.94%	2.36945E-13	0.03%	1.68407E-13	0.02%	1.40821E-14	0.00%
GW	kg CO2 eq	0.092808189	0.081824615	88.17%	0.006212239	6.69%	0.004404418	4.75%	0.000366917	0.40%
PS	kg O3 eq	0.006211324	0.002526675	40.68%	0.001015562	16.35%	0.002560958	41.23%	0.000108129	1.74%
AC	kg SO2 eq	0.000614793	0.000495727	80.63%	3.70936E-05	6.03%	7.84237E-05	12.76%	3.54895E-06	0.58%
EU	kg N eq	0.000176764	0.000169726	96.02%	2.06735E-06	1.17%	4.76324E-06	2.69%	2.07929E-07	0.12%
HHC	CTUh	6.59961E-10	5.09365E-10	77.18%	8.50741E-11	12.89%	6.04658E-11	9.16%	5.05612E-12	0.77%
HHNC	CTUh	8.52525E-09	7.07452E-09	82.98%	8.19539E-10	9.61%	5.82481E-10	6.83%	4.87068E-11	0.57%
RE	kg PM2.5 eq	2.90644E-05	2.68898E-05	92.52%	6.46166E-07	2.22%	1.46165E-06	5.03%	6.67175E-08	0.23%
EC	CTUe	2.383981777	2.355922578	98.82%	0.015851093	0.66%	0.011266045	0.47%	0.000942061	0.04%
FF	MJ surplus	0.098890529	0.077820306	78.69%	0.011902908	12.04%	0.008459902	8.55%	0.000707413	0.72%

Table B47. TRACI Environmental Impacts of thraustochytrid meal based on unit mass (1 kg) meal production.

Impact category	Unit	Total	Glucose GLO | market for glucose | APOS, U		Electricity, at grid, US, 2010/kWh/RNA (Freeze drying)		Electricity, at grid, US, 2010/kWh/RNA (Other)	
OD	kg CFC-11 eq	2.44E-07	2.42E-07	99.36%	1.41E-09	0.58%	1.57E-10	0.06%
GW	kg CO2 eq	99.38494	2.2104	2.22%	87.45708	88.00%	9.717454	9.78%
PS	kg O3 eq	5.687381	0.126389	2.22%	5.004893	88.00%	0.556099	9.78%
AC	kg SO2 eq	0.851377	0.015326	1.80%	0.752446	88.38%	0.083605	9.82%
EU	kg N eq	0.036501	0.025202	69.04%	0.010169	27.86%	0.00113	3.10%
HHC	CTUh	3.76E-07	1.79E-07	47.70%	1.77E-07	47.07%	1.97E-08	5.23%
HHNC	CTUh	6.06E-06	2.75E-06	45.49%	2.97E-06	49.06%	3.3E-07	5.45%
RE	kg PM2.5 eq	0.044207	0.002223	5.03%	0.037786	85.47%	0.004198	9.50%
EC	CTUe	72.53755	24.62367	33.95%	43.1225	59.45%	4.791388	6.61%
FF	MJ surplus	86.64208	2.407557	2.78%	75.81107	87.50%	8.423452	9.72%

Table B48. Results from t-test analysis (confidence level = 95) for t-value (t) and p-value (p) among FMOC diets versus fish meal and fish oil replacement alternatives.

(a)

	Compare Aquafeed → With Aquafeed ↓	FMOC-1	FMOC-2	FMOC-3	FMOC-4
AC	FMF-1-T	t = 2.8*10^3 p = 0.0000	t = -5.0*10^2 p = 0.0000	t = 132.1246 p = 0.0000	t = 88.1277 p = 0.0000
	FMF-2-T	t = -6*10^3 p = 0.0000	t = -7.3*10^3 p = 0.0000	t = -8.1*10^3 p = 0.0000	t = -3.8*10^3 p = 0.0000
	FMF-3-P	t = 858.15.66 p = 0.0000	t = -2.4*10^2 p = 0.0000	t = -13.3592 p = 0.0000	t = 28.5050 p = 0.0000
	FMF-4-P	t = 3.9*10^3 p = 0.0000	t = 212.7353 p = 0.0000	t = 1.4*10^3 p = 0.0000	t = 376.3957 p = 0.0000
	FMF-5-S	t = 3.9*10^3 p = 0.0000	t = 87.3355 p = 0.0000	t = 1.2*10^3 p = 0.0000	t = 327.1471 p = 0.0000
	FOF-1	t = 1.2*10^3 p = 0.0000	t = -1.3*10^3 p = 0.0000	t = 159.7324 p = 0.0000	t = 145.6926 p = 0.0000
	FOF-2	t = -4.2*10^3 p = 0.0000	t = -5.5*10^3 p = 0.0000	t = -5.7*10^3 p = 0.0000	t = -3.2*10^3 p = 0.0000
	FMOF	t = 1.4*10^3 p = 0.0000	t = -1.7*10^3 p = 0.0000	t = -2.0*10^3 p = 0.0000	t = -3.9*10^2 p = 0.0000

(b)

	Compare Aquafeed → With Aquafeed ↓	FMOC-1	FMOC-2	FMOC-3	FMOC-4
HHC	FMF-1-T	t = 38.3652 p = 0.0000	t = 6.9030 p = 0.0000	t = 37.7967 p = 0.0000	t = 32.8945 p = 0.0000
	FMF-2-T	t = -1.2*10^2 p = 0.0000	t = -1.5*10^2 p = 0.0000	t = -1.3*10^2 p = 0.0000	t = -37.1504 p = 0.0000
	FMF-3-P	t = -6.0056 p = 0.0000	t = -41.1249 p = 0.0000	t = -9.3141 p = 0.0000	t = 14.0835 p = 0.0000

	FMF-4-P	t = 75.1495 p = 0.0000	t = 29.4008 p = 0.0000	t = 72.0682 p = 0.0000	t = 41.4132 p = 0.0000
	FMF-5-S	t = 5.9858 p = 0.0000	t = -18.1035 p = 0.0000	t = 3.9777 p = 0.0001	t = 18.2631 p = 0.0000
	FOF-1	t = 10.1779 p = 0.0000	t = -24.5146 p = 0.0000	t = 7.2536 p = 0.0000	t = 20.3890 p = 0.0000
	FOF-2	t = -29.6015 p = 0.0000	t = -54.9605 p = 0.0000	t = -32.2788 p = 0.0000	t = -0.0981 p = 0.9219
	FMOF	t = 5.5569 p = 0.0000	t = -12.9366 p = 0.0000	t = 3.7735 p = 0.0000	t = 17.0878 p = 0.0000

(c)

	Compare Aquafeed → With Aquafeed ↓	FMOC-1	FMOC-2	FMOC-3	FMOC-4
EC	FMF-1-T	t = 321.1784 p = 0.0000	t = -42.7006 p = 0.0000	t = 2.8*10^3 p = 0.0000	t = 97.1255 p = 0.0000
	FMF-2-T	t = -5.8*10^2 p = 0.0000	t = -6.4*10^2 p = 0.0000	t = 526.0185 p = 0.0000	t = -4.6*10^3 p = 0.0000
	FMF-3-P	t = 266.6164 p = 0.0000	t = -31.7020 p = 0.0000	t = 2.1*10^3 p = 0.0000	t = 97.3655 p = 0.0000
	FMF-4-P	t = 498.8942 p = 0.0000	t = 27.8763 p = 0.0000	t = 3.5*10^3 p = 0.0000	t = 156.6172 p = 0.0000
	FMF-5-S	t = 277.0676 p = 0.0000	t = -41.0516 p = 0.0000	t = 2.3*10^3 p = 0.0000	t = 93.1352 p = 0.0000
	FOF-1	t = 164.4797 p = 0.0000	t = -18.9221 p = 0.0000	t = 1.2*10^3 p = 0.0000	t = 81.8012 p = 0.0000
	FOF-2	t = 52.9072 p = 0.0000	t = -74.0278 p = 0.0000	t = 791.5659 p = 0.0000	t = 11.0708 p = 0.0000
	FMOF	t = -8*10^2 p = 0.0000	t = -7.2*10^2 p = 0.0000	t = 1.4*10^3 p = 0.0000	t = -4.5*10^2 p = 0.0000

(d)

	Compare Aquafeed → With Aquafeed ↓	FMOC-1	FMOC-2	FMOC-3	FMOC-4
EU	FMF-1-T	t = 608.5336 p = 0.0000	t = -63.5092 p = 0.0000	t = 415.2933 p = 0.0000	t = 183.3348 p = 0.0000
	FMF-2-T	t = -1.6*10^3 p = 0.0000	t = -1.9*10^3 p = 0.0000	t = -2.2*10^3 p = 0.0000	t = -7.7*10^2 p = 0.0000
	FMF-3-P	t = 143.2765 p = 0.0000	t = -1.2*10^2 p = 0.0000	t = 18.1788 p = 0.0000	t = 76.9369 p = 0.0000
	FMF-4-P	t = 866.1645 p = 0.0000	t = 95.6936 p = 0.0000	t = 830.5637 p = 0.0000	t = 250.5369 p = 0.0000
	FMF-5-S	t = 654.1815 p = 0.0000	t = -55.6897 p = 0.0000	t = 485.7431 p = 0.0000	t = 188.5694 p = 0.0000
	FOF-1	t = 196.7555 p = 0.0000	t = -1.0*10^2 p = 0.0000	t = 58.0782 p = 0.0000	t = 103.6513 p = 0.0000
	FOF-2	t = 176.8629 p = 0.0000	t = -1.3*10^2 p = 0.0000	t = 34.9847 p = 0.0000	t = 89.8558 p = 0.0000
	FMOF	t = 213.3393 p = 0.0000	t = -4.2*10^2 p = 0.0000	t = -2.1*10^2 p = 0.0000	t = 41.4420 p = 0.0000

(e)

	Compare Aquafeed → With Aquafeed ↓	FMOC-1	FMOC-2	FMOC-3	FMOC-4
FF	FMF-1-T	t = 1.3*10^3 p = 0.0000	t = 283.4121 p = 0.0000	t = 809.6480 p = 0.0000	t = 451.2394 p = 0.0000
	FMF-2-T	t = -1.2*10^3 p = 0.0000	t = -1.7*10^3 p = 0.0000	t = -1.1*10^3 p = 0.0000	t = -9.3*10^2 p = 0.0000
	FMF-3-P	t = 563.4666 p = 0.0000	t = -70.0873 p = 0.0000	t = 419.9438 p = 0.0000	t = 254.7039 p = 0.0000
	FMF-4-P	t = 1.2*10^3 p = 0.0000	t = 300.8728 p = 0.0000	t = 808.6943 p = 0.0000	t = 462.0260 p = 0.0000

	FMF-5-S	t = 1.4*10^3 p = 0.0000	t = 299.5048 p = 0.0000	t = 833.4322 p = 0.0000	t = 451.9799 p = 0.0000
	FOF-1	t = 760.0015 p = 0.0000	t = 12.0408 p = 0.0000	t = 543.3146 p = 0.0000	t = 320.7934 p = 0.0000
	FOF-2	t = -3.8*10^3 p = 0.0000	t = -4.6*10^3 p = 0.0000	t = -3.2*10^3 p = 0.0000	t = -2.3*10^3 p = 0.0000
	FMOF	t = 374.7900 p = 0.0000	t = -5.8*10^2 p = 0.0000	t = 208.1489 p = 0.0000	t = 75.3644 p = 0.0000

(f)

GW	Compare Aquafeed → With Aquafeed ↓	FMOC-1	FMOC-2	FMOC-3	FMOC-4
	FMF-1-T	t = 3.2*10^3 p = 0.0000	t = -5.2*10^2 p = 0.0000	t = 3.8*10^3 p = 0.0000	t = 763.2482 p = 0.0000
	FMF-2-T	t = -4.1*10^3 p = 0.0000	t = -5.8*10^3 p = 0.0000	t = -3.7*10^3 p = 0.0000	t = -3.0*10^3 p = 0.0000
	FMF-3-P	t = 1.4*10^3 p = 0.0000	t = -1.1*10^2 p = 0.0000	t = 1.7*10^3 p = 0.0000	t = 657.9867 p = 0.0000
	FMF-4-P	t = 4.3*10^3 p = 0.0000	t = 329.5710 p = 0.0000	t = 4.9*10^3 p = 0.0000	t = 1.2*10^3 p = 0.0000
	FMF-5-S	t = 5.2*10^3 p = 0.0000	t = 152.8124 p = 0.0000	t = 5.8*10^3 p = 0.0000	t = 1.1*10^3 p = 0.0000
	FOF-1	t = 2.2*10^3 p = 0.0000	t = -64.2489 p = 0.0000	t = 2.6*10^3 p = 0.0000	t = 842.5341 p = 0.0000
	FOF-2	t = -5.1*10^3 p = 0.0000	t = -6.9*10^3 p = 0.0000	t = -4.6*10^3 p = 0.0000	t = -3.4*10^3 p = 0.0000
	FMOF	t = 2.0*10^3 p = 0.0000	t = -2.1*10^3 p = 0.0000	t = 2.8*10^3 p = 0.0000	t = 181.6591 p = 0.0000

(g)

	Compare Aquafeed → With Aquafeed ↓	FMOC-1	FMOC-2	FMOC-3	FMOC-4
HHNC	FMF-1-T	t = 582.0755 p = 0.0000	t = -36.6344 p = 0.0000	t = 298.0776 p = 0.0000	t = 152.6098 p = 0.0000
	FMF-2-T	t = -1.2*10^3 p = 0.0000	t = -9.7*10^2 p = 0.0000	t = -1.6*10^3 p = 0.0000	t = -6.3*10^2 p = 0.0000
	FMF-3-P	t = 382.1347 p = 0.0000	t = -1.1*10^2 p = 0.0000	t = 40.7003 p = 0.0000	t = 94.9329 p = 0.0000
	FMF-4-P	t = 460.6220 p = 0.0000	t = -14.4108 p = 0.0000	t = 220.8862 p = 0.0000	t = 161.7872 p = 0.0000
	FMF-5-S	t = 721.0451 p = 0.0000	t = 21.28868 p = 0.0000	t = 497.0975 p = 0.0000	t = 197.7932 p = 0.0000
	FOF-1	t = 146.0250 p = 0.0000	t = -69.5642 p = 0.0000	t = 15.8639 p = 0.0000	t = 74.9806 p = 0.0000
	FOF-2	t = 148.7097 p = 0.0000	t = -90.7657 p = 0.0000	t = -2.0617 p = 0.0394	t = 67.3136 p = 0.0000
	FMOF	t = 504.4511 p = 0.0000	t = -77.8543 p = 0.0000	t = 171.9841 p = 0.0000	t = 121.2893 p = 0.0000

(h)

	Compare Aquafeed → With Aquafeed ↓	FMOC-1	FMOC-2	FMOC-3	FMOC-4
OD	FMF-1-T	t = 156.8340 p = 0.0000	t = 45.0625 p = 0.0000	t = 31.7987 p = 0.0000	t = 140.3055 p = 0.0000
	FMF-2-T	t = -2.2*10^2 p = 0.0000	t = -2.8*10^2 p = 0.0000	t = -5.0*10^2 p = 0.0000	t = -0.8856 p = 0.3759
	FMF-3-P	t = 75.1649 p = 0.0000	t = 0.0043 p = 0.9966	t = -29.2626 p = 0.0000	t = 115.1435 p = 0.0000
	FMF-4-P	t = 162.8011 p = 0.0000	t = 58.9555 p = 0.0000	t = 53.8788 p = 0.0000	t = 145.9964 p = 0.0000

	FMF-5-S	t = 200.4730 p = 0.0000	t = 75.1481 p = 0.0000	t = 100.6662 p = 0.0000	t = 152.5658 p = 0.0000
	FOF-1	t = 19.2798 p = 0.0000	t = -38.4718 p = 0.0000	t = -67.2530 p = 0.0000	t = 86.1252 p = 0.0000
	FOF-2	t = 1.2208 p = 0.2223	t = -48.3185 p = 0.0000	t = -72.7916 p = 0.0000	t = 72.6195 p = 0.0000
	FMOF	t = 39.4234 p = 0.0000	t = -48.3533 p = 0.0000	t = -1.2*10^2 p = 0.0000	t = 98.7840 p = 0.0000

(i)

RE	Compare Aquafeed → With Aquafeed ↓	FMOC-1	FMOC-2	FMOC-3	FMOC-4
	FMF-1-T	t = 956.4753 p = 0.0000	t = 26.8552 p = 0.0000	t = 37.9088 p = 0.0000	t = 338.0077 p = 0.0000
	FMF-2-T	t = -2.7*10^3 p = 0.0000	t = -3.1*10^3 p = 0.0000	t = -3.7*10^3 p = 0.0000	t = -1.4*10^3 p = 0.0000
	FMF-3-P	t = 448.0311 p = 0.0000	t = -86.4645 p = 0.0000	t = -95.7845 p = 0.0000	t = 229.0152 p = 0.0000
	FMF-4-P	t = 1.3*10^03 p = 0.0000	t = 249.4787 p = 0.0000	t = 359.2617 p = 0.0000	t = 441.6396 p = 0.0000
	FMF-5-S	t = 1.4*10^03 p = 0.0000	t = 265.4947 p = 0.0000	t = 417.2609 p = 0.0000	t = 446.7801 p = 0.0000
	FOF-1	t = 451.6609 p = 0.0000	t = -1.0*10^2 p = 0.0000	t = -1.1*10^2 p = 0.0000	t = 223.8754 p = 0.0000
	FOF-2	t = -2.5*10^3 p = 0.0000	t = -2.8*10^3 p = 0.0000	t = -3.1*10^3 p = 0.0000	t = -1.6*10^3 p = 0.0000
	FMOF	t = 440.0479 p = 0.0000	t = -4.7*10^2 p = 0.0000	t = -6.9*10^2 p = 0.0000	t = 117.5760 p = 0.0000

(j)

PS	Compare Aquafeed → With Aquafeed ↓	FMOC-1	FMOC-2	FMOC-3	FMOC-4
	FMF-1-T	t = 1.1*10^3 p = 0.0000	t = 502.4316 p = 0.0000	t = 858.6961 p = 0.0000	t = 668.6170 p = 0.0000
	FMF-2-T	t = -4.7*10^2 p = 0.0000	t = -7.8*10^2 p = 0.0000	t = -4.8*10^2 p = 0.0000	t = -4.1*10^2 p = 0.0000
	FMF-3-P	t = 334.4744 p = 0.0000	t = -39.4891 p = 0.0000	t = 278.3126 p = 0.0000	t = 266.4281 p = 0.0000
	FMF-4-P	t = 959.7852 p = 0.0000	t = 379.4280 p = 0.0000	t = 759.7099 p = 0.0000	t = 607.7359 p = 0.0000
	FMF-5-S	t = 1.3*10^3 p = 0.0000	t = 594.8884 p = 0.0000	t = 924.2708 p = 0.0000	t = 679.5714 p = 0.0000
	FOF-1	t = 534.1859 p = 0.0000	t = 20.6194 p = 0.0000	t = 429.0864 p = 0.0000	t = 374.0537 p = 0.0000
	FOF-2	t = -4.7*10^3 p = 0.0000	t = -5.7*10^3 p = 0.0000	t = -4.2*10^3 p = 0.0000	t = -3.3*10^3 p = 0.0000
	FMOF	t = 436.3214 p = 0.0000	t = -3.7*10^2 p = 0.0000	t = 291.1698 p = 0.0000	t = 243.6800 p = 0.0000

(k)

WI	Compare Aquafeed → With Aquafeed ↓	FMOC-1	FMOC-2	FMOC-3	FMOC-4
	FMF-1-T	t = 4.4814 p = 0.0000	t = 6.3789 p = 0.0000	t = 27.4875 p = 0.0000	t = 5.7590 p = 0.0000
	FMF-2-T	t = -20.1697 p = 0.0000	t = -16.3585 p = 0.0000	t = -5.3079 p = 0.0000	t = -6.4846 p = 0.0000
	FMF-3-P	t = -14.9435 p = 0.0000	t = -11.5258 p = 0.0000	t = 0.7400 p = 0.4594	t = -3.7633 p = 0.0002
	FMF-4-P	t = 2.3063 p = 0.0212	t = 4.5361 p = 0.0000	t = 26.5683 p = 0.0000	t = 4.8172 p = 0.0000

	FMF-5-S	t = 8.9506 p = 0.0000	t = 10.3099 p = 0.0000	t = 35.7472 p = 0.0000	t = 7.4963 p = 0.0000
	FOF-1	t = -2.2998 p = 0.0216	t = -6061 p = 0.5445	t = 9.4566 p = 0.0000	t = 1.8879 p = 0.0592
	FOF-2	t = 11.1946 p = 0.0000	t = 12.1164 p = 0.0000	t = 20.7810 p = 0.0000	t = 10.9298 p = 0.0000
	FMOF	t = -54.9927 p = 0.0000	t = -46.6706 p = 0.0000	t = -43.0908 p = 0.0000	t = -21.0925 p = 0.0000

Table B49. Calculated BRU (gC / kg Aquafeed) for investigated diets.

FMOC-1		
Ingredient	g/kg	BRU (g C / kg feed)
Mixed Nut Meal	0	0
Poultry Meal	160	288.3217951
Wheat Flour	195.1	89.746
Menhaden Meal	195	2473.827546
Fish Oil (whitefish Trimming oil)	0	0
Fish Oil (menhaden)	157.4	21965.05135
Soy Protein Concentrate	128.5	90.464
Blood Meal	70.5	127.041791
Canola Oil	56.5	57.178
Corn Protein Concentrate	0	0
Dicalcium phosphate	5	0
Vitamin Premix	10	0
Lysine-HCL	6.5	0
Choline CL	6	0
Taurine	0	0
DL-Methionine	4	0
Stay-C	2	0
Threonine	1.5	0

Trace Minerals Premix	1	0
Astaxanthin (Dye)	1	0
Total BRU (gC / kg feed)	25091.63048	
FMOC-2		
Ingredient	g/kg	BRU (g C / kg feed)
Fish meal	250	3171.573777
Soybean meal	56.2	29.6736
Casein	143.2	0
Wheat Gluten	100	328.6
Canola oil	78.2	79.1384
Fish oil	91.4	12754.8011
Thraustochytrid meal	0	0
Pregelatinized starch	136.2	62.652
Vitamin mix	3	0
Stay C	3	0
Choline CL	2	0
Mineral mix	5	0
Calsium phosphate	21.8	0
Cellulose	50	22.2
Bentonite	49	0
CMC (Carboxymethyl Cellulose)	9	3.591
Cholestane	1	0
Yttrium oxide	1	0
Total BRU (gC / kg feed)	16452.22988	
FMOC-3		
Ingredient	g/kg	BRU (g C / kg feed)
Fish meal	108	1370.119872
Soybean meal	450	237.6
Wheat pollards	126	48.51
Rice bran	200	88.8
Dicalcium phosphate	46	0

Fish oil	18	2511.886432
Methionine	2	0
Limestone	24	0
Vitamin/Mineral premix	26	0
Total BRU (gC / kg feed)	4256.916303	
FMOC-4		
Ingredient	g/kg	BRU (g C / kg feed)
Soy protein concentrate	190	117.8
Wheat gluten	90	295.74
Corn gluten	36	0.936
Vegetable protein (other resources)	86	87.032
Rapeseed oil	201	305.0175
Wheat starch	89	40.94
Pea starch and undefined plant carbohydrate	18	0
marine protein, forage	117	1484.296528
marine protein, trimming	28	124.3256921
fish oil, forage	78	10884.8412
fish oil, trimming	26	1269.89814
Vitamins, minerals, amino acids, etc.	40	0
Total BRU (gC / kg feed)	14610.82706	
FMF-1-T		
Ingredient	g/kg	BRU (g C / kg feed)
Menhaden meal	0	0
Poultry by-product meal	147	3644.964133
Soybean meal	500	264
Menhaden oil	51.5	7186.786179
Corn starch	53.8	25.017
Whole wheat	160	73.6
Corn gluten meal	50	1.3
Lecithin	10	9.42

Mineral premix	2.5	0
Vitamin premix	5	0
Choline Cl	2	0
Stay C	1	0
CaPO4	16	0
Dl-methionine	1.2	0
Total BRU (gC / kg feed)	11205.08731	
FMF-2-T		
Ingredient	g/kg	BRU (g C / kg feed)
Blood meal	300	540.6033658
Wheat bran	460	25.3
Corn starch	100	46.5
Sardine oil	15	2093.238693
Soybean oil	15	43.2
Vitamin mix	10	0
Mineral mix	10	0
Monocalcium phosphate	20	0
Alpha cellulose	70	31.08
Total BRU (gC / kg feed)	2779.922059	
FMF-3-P		
Ingredient	g/kg	BRU (g C / kg feed)
Corn gluten meal	360	9.36
Yellow corn	152	70.68
Corn gluten feed	125	279
Peanut meal	204	157.896
Soybean oil	7	20.16
Menhadden oil	95	13257.17839
Lysine	10.2	0
Methionine	1.7	0
Dicalcium phosphate	32.7	0
Vitamin premix	3	0

Mineral premix	1.5	0
Vitamin C	1	0
Choline Cl	7	0
Total BRU (gC / kg feed)	13794.27439	
FMF-4-P		
Ingredient	g/kg	BRU (g C / kg feed)
Corn gluten meal	227	119.856
Yellow corn	184	85.56
Corn gluten feed	32	71.424
Soybean meal	403	212.784
Soybean oil	7	20.16
Menhaden oil	95	13257.17839
Lysine	1.3	0
Methionine	2.4	0
Dicalcium phosphate	35.6	0
Vitamin premix	3	0
Mineral premix	1.5	0
Vitamin C	1	0
Choline Cl	7	0
Total BRU (gC / kg feed)	13766.96239	
FMF-5-S		
Ingredient	g/kg	BRU (g C / kg feed)
Alaskan pollock fish meal	152.95	679.1290929
Menhaden oil	29	4046.92814
Wheat starch	13.85	6.371
Whole wheat flour	555	255.3
Vital wheat gluten	40	131.44
Brewers yeast	50	0
Squid liver powder	25	0
Soybean meal	90	47.52
Soy lecithin	20	18.84

Cholesterol	2.4	0
Vitamin premix	4	0
Choline Cl	1.2	0
Vitamin C	0.8	0
Phosphate minerals (as Sodium)	16.8	0
Total BRU (gC / kg feed)	5185.528233	
FOF-1		
Ingredient	g/kg	BRU (g C / kg feed)
Fish meal	250	3171.573777
Soybean meal	56.2	29.6736
Casein	143.2	0
Wheat Gluten	100	328.6
Canola oil	169.6	171.6352
Fish oil	0	0
Thraustochytrid meal	0	0
Pregelatinized starch	150	69
Vitamin mix	3	0
Stay C	3	0
Choline CL	2	0
Mineral mix	5	0
Calsium phosphate	21.8	0
Cellulose	36.2	16.0728
Bentonite	49	0
CMC (Carboxymethyl Cellulose)	9	3.591
Cholestane	1	0
Yttrium oxide	1	0
Total BRU (gC / kg feed)	3790.146377	
FOF-2		
Ingredient	g/kg	BRU (g C / kg feed)
Fish meal	250	3171.573777
Soybean meal	36.5	19.272

Casein	132.9	0
Wheat Gluten	100	328.6
Canola oil	110.5	111.826
Fish oil	0	0
Thraustochytrid oil	100	0
Pregelatinized starch	150	67.5
Vitamin mix	3	0
Stay C	3	0
n	2	0
Mineral mix	5	0
Calsium phosphate	23	0
Cellulose	24.2	10.7448
Bentonite	49	0
CMC (Carboxymethyl Cellulose)	9	3.591
Cholestane	1	0
Yttrium oxide	1	0
Total BRU (gC / kg feed)	3713.107577	
FMOF		
Ingredient	g/kg	BRU (g C / kg feed)
Mixed Nut Meal	320	240.64
Poultry Meal	295	531.5933097
Wheat Flour	99.4	45.724
Menhaden Meal	0	0
Fish Oil (whitefish Trimming oil)	182	8889.286983
Fish Oil (menhaden)	0	0
Soy Protein Concentrate	0	0
Blood Meal	0	0
Canola Oil	0	0
Corn Protein Concentrate	35.6	0
Dicalcium phosphate	32.5	0
Vitamin Premix	10	0

Lysine-HCL	6.2	0
Choline CL	6	0
Taurine	5	0
DL-Methionine	2.8	0
Stay-C	3	0
Threonine	0.5	0
Trace Minerals Premix	1	0
Astaxanthin	1	0
Total BRU (gC / kg feed)	9707.244292	

Appendix C

Supplementary Information (SI) for chapter 5.

Table C50. Life cycle inventory for 2015 year-round operation of aquaponic system (Tilapia Production).

Process	Section	Material	Amount	Unit	Database	Comment
One-year Aquaponic system Operation	Input	Fish food	1376.442	kg	Measured	Rangen tilapia
		Water	427,188	kg	Inputs from nature/ groundwater	Delaide *et al*. 2017 One-time annual fill + 3% daily water loss
		Electricity	5370.105	kWh	Measured	Montello Facility Co.
		Heat	2382.781	m^3	USLCI	Natural gas, Deru *et al*. 2007 (kWh to m^3)
		Seed	46.420	g	Agri-footprint - mass allocation	johnnyseeds.com, 1lb = 99200 seeds
		Infrastructure	6	p	Measured	Nelson & Pade
	Outputs	Fish	555.871	kg	Measured	Live-weight
		Kale	7.626	kg	Measured	Top of plant
		Butterhead	12.966	kg	Measured	Top of plant
		Pak Choi	38.280	kg	Measured	Top of plant
		Romaine	32.210	kg	Measured	Top of plant
		Solids waste	290.557	kg	Ecoinvent 3 APOS	Rakocy *et al.* 2007 Municipal biowaste
1 kg Fish food (tilapia)	input	Soybean meal	0.400	kg	Agri-Footprint – mass allocation	Boxman *et al.* 2015
		Wheat middling	0.171	kg	Agri-Footprint – mass allocation	Boxman *et al.* 2015
		Maize/ Corn	0.171	kg	Agri-Footprint – mass allocation	Boxman *et al.* 2015
		Fish meal	0.057	kg	Agri-Footprint – mass allocation	Boxman *et al.* 2015
1 kWh Energy (2016 resources)	input	Natural gas	0.38	kWh	USLCI	EIA, Alliant Energy
		Coal	0.37	kWh	USLCI	EIA, Alliant Energy

		Nuclear	0.06	kWh	USLCI	EIA, Alliant Energy
		Oil	0.04	kWh	USLCI	EIA, Alliant Energy
		Renewables	0.15	kWh	Calculated	EIA, Alliant Energy
1 kWh Renewables	inputs	Wind	0.64	kWh	ELCD	WASAL
		Solar	0.01	kWh	Ecoinvent 3 APOS	WASAL
		Biomass	0.19	kWh	USLCI	WASAL
		Hydro-electric	0.17	kWh	Ecoinvent 3 APOS	WASAL
1 lab infrastructure (modified based on one-year operation)	inputs	Fish tanks	4.115	kg	Ecoinvent 3 APOS	Assmann Co., Polytank Co., HDPE material acquisition & manufacturing (injection moulding)
		Clarifiers	1.402	kg	Ecoinvent 3 APOS	
		Mineralization tanks	1.402	kg	Ecoinvent 3 APOS	
		Degas tanks	0.301	kg	Ecoinvent 3 APOS	
		Raft tanks	2.805	kg	Ecoinvent 3 APOS	
		Sump tank	0.197	kg	Ecoinvent 3 APOS	
		Rockwool grow cubes	9.422	kg	ELCD	Nelson & Pade Inc.
		Raft trays	1.083	kg	ELCD	Expanded polystyrene (EPS), Granulate production
		Fishnets	0.045	kg	Ecoinvent 3 APOS	Nylon production and manufacturing (extrusion)
		Water Pump	1/7	p	Ecoinvent 3 APOS	Nelson & Pade Inc.
		Lights	2	p	Ecoinvent 3 APOS	Nelson & Pade Inc.

Table C51. Life cycle inventory for 2016 year-round operation of aquaponic system (conventional Walleye Production).

Process	Section	Material	Amount	Unit	Database	Comment
One-year Aquaponic system Operation	Input	Fish food	1899.000	kg	Measured	Skretting, Europa Co.
		Water	427,188	kg	Inputs from nature/ groundwater	Delaide *et al*. 2017

						One-time annual fill + 3% daily water loss
		Electricity	6657.596	kWh	Measured	Montello Facility Co.
		Heat	3050.290	m^3	USLCI	Natural gas, Deru *et al*. 2007 (kWh to m^3)
		Seed	46.420	g	Agri-footprint - mass allocation	johnnyseeds.com, 1lb = 99200 seeds
		Lab infrastructure	6	p	Measured	Nelson & Pade
	Outputs	Fish	350.640	kg	Measured	Live-weight
		Kale	74.542	kg	Measured	Top of plant
		Butterhead	167.545	kg	Measured	Top of plant
		Pak Choi	376.435	kg	Measured	Top of plant
		Romaine	219.401	kg	Measured	Top of plant
		Solids waste	548.261	kg	Ecoinvent 3 APOS	Rakocy *et al.* 2007 Municipal biowaste
1 kg Fish food (Skretting, Norway)	input	Fishmeal	0.560	kg	Agri-Footprint – mass allocation	Bjerkeng *et al*. 1997
		Soymeal	0.088	kg	Agri-Footprint – mass allocation	Bjerkeng *et al*. 1997
		Capelin Oil	0.219	kg	Agri-Footprint – mass allocation	Bjerkeng *et al*. 1997 Soler-Vila *et.al.* 2009
		Wheat Starch	0.097	kg	Agri-Footprint – mass allocation	Bjerkeng *et al*. 1997 Soler-Vila *et.al.* 2009
1 kWh Energy (2016 resources)	input	Natural gas	0.38	kWh	USLCI	EIA, Alliant Energy
		Coal	0.37	kWh	USLCI	EIA, Alliant Energy
		Nuclear	0.06	kWh	USLCI	EIA, Alliant Energy
		Oil	0.04	kWh	USLCI	EIA, Alliant Energy
		Renewables	0.15	kWh	Calculated	EIA, Alliant Energy

1 kWh Renewables	inputs	Wind	0.64	kWh	ELCD	WASAL
		Solar	0.01	kWh	Ecoinvent 3 APOS	WASAL
		Biomass	0.19	kWh	USLCI	WASAL
		Hydro-electric	0.17	kWh	Ecoinvent 3 APOS	WASAL
1 lab infrastructure (modified based on one-year operation)	inputs	Fish tanks	4.115	kg	Ecoinvent 3 APOS	Assmann Co., Polytank Co., HDPE material acquisition & manufacturing (injection moulding)
		Clarifiers	1.402	kg	Ecoinvent 3 APOS	
		Mineralization tanks	1.402	kg	Ecoinvent 3 APOS	
		Degas tanks	0.301	kg	Ecoinvent 3 APOS	
		Raft tanks	2.805	kg	Ecoinvent 3 APOS	
		Sump tank	0.197	kg	Ecoinvent 3 APOS	
		Rockwool grow cubes	9.422	kg	ELCD	Nelson & Pade Inc.
		Raft trays	1.083	kg	ELCD	Expanded polystyrene (EPS), Granulate production
		Fishnets	0.045	kg	Ecoinvent 3 APOS	Nylon production and manufacturing (extrusion)
		Water Pump	1/7	p	Ecoinvent 3 APOS	Nelson & Pade Inc.
		Lights	2	p	Ecoinvent 3 APOS	Nelson & Pade Inc.

Table C52. Life cycle inventory for 2017 year-round operation of aquaponic system (Hybrid Walleye Production).

Process	Section	Material	Amount	Unit	Database	Comment
One-year Aquaponic system Operation	Input	Fish food	968.365	kg	Measured	Skretting, Europa Co.
		Water	427,188	kg	Inputs from nature/ groundwater	Delaide *et al*. 2017 One-time annual fill + 3% daily water loss
		Electricity	8614.652	kWh	Measured	Montello Facility Co.
		Heat	3502.359	m^3	USLCI	Natural gas,

						Deru *et al*. 2007 (kWh to m^3)
		Seed	46.420	g	Agri-footprint - mass allocation	johnnyseeds.com, 1lb = 99200 seeds
		Lab infrastructure	6	p	Measured	Nelson & Pade
	Outputs	Fish	284.669	kg	Measured	Live-weight
		Kale	212.148	kg	Measured	Top of plant
		Butterhead	227.440	kg	Measured	Top of plant
		Pak Choi	415.854	kg	Measured	Top of plant
		Romaine	310.207	kg	Measured	Top of plant
		Solids waste	242.091	kg	Ecoinvent 3 APOS	Rakocy *et al*. 2007 Municipal biowaste
1 kg Fish food (Skretting, Norway)	input	Fishmeal	0.560	kg	Agri-Footprint – mass allocation	Bjerkeng *et al*. 1997
		Soymeal	0.088	kg	USLCI	Bjerkeng *et al*. 1997
		Capelin Oil	0.219	kg	Agri-Footprint – mass allocation	Bjerkeng *et al*. 1997 Soler-Vila *et.al*. 2009
		Wheat Starch	0.097	kg	Agri-Footprint – mass allocation	Bjerkeng *et al*. 1997 Soler-Vila *et.al*. 2009
1 kWh Energy (2016 resources)	input	Natural gas	0.38	kWh	USLCI	EIA, Alliant Energy
		Coal	0.37	kWh	USLCI	EIA, Alliant Energy
		Nuclear	0.06	kWh	USLCI	EIA, Alliant Energy
		Oil	0.04	kWh	USLCI	EIA, Alliant Energy
		Renewables	0.15	kWh	Calculated	EIA, Alliant Energy
1 kWh Renewables	inputs	Wind	0.64	kWh	ELCD	WASAL
		Solar	0.01	kWh	Ecoinvent 3 APOS	WASAL
		Biomass	0.19	kWh	USLCI	WASAL
		Hydro-electric	0.17	kWh	Ecoinvent 3 APOS	WASAL

1 lab infrastructure (modified based on one-year operation)	inputs	Fish tanks	4.115	kg	Ecoinvent 3 APOS	Assmann Co., Polytank Co., HDPE material acquisition & manufacturing (injection moulding)
		Clarifiers	1.402	kg	Ecoinvent 3 APOS	
		Mineralization tanks	1.402	kg	Ecoinvent 3 APOS	
		Degas tanks	0.301	kg	Ecoinvent 3 APOS	
		Raft tanks	2.805	kg	Ecoinvent 3 APOS	
		Sump tank	0.197	kg	Ecoinvent 3 APOS	
		Rockwool grow cubes	9.422	kg	ELCD	Nelson & Pade Inc.
		Raft trays	1.083	kg	ELCD	Expanded polystyrene (EPS), Granulate production
		Fishnets	0.045	kg	Ecoinvent 3 APOS	Nylon production and manufacturing (extrusion)
		Water Pump	1/7	p	Ecoinvent 3 APOS	Nelson & Pade Inc.
		Lights	2	p	Ecoinvent 3 APOS	Nelson & Pade Inc.

Table C53. Aquaponics infrastructure costs (6 aquaponics labs).

Item	Item Specifocations	Quantity	Unit	Unit Price ($US)	Total Price ($US)	Lifetime	Comments / References
Fish Tank	Diameter: 75, Depth: 30, Capacity=450 Gal	12	p	544.83	6537.96	20	PolyTank Co.
Fish Tank Net	Nylon high impact net, Black, 3/4" Square Mesh	12	p	4.92	59.00	20	Just For Nets
Clarifier Tank	Diameter: 36, Depth: 32, Capacity=130 Gal	12	p	351.5	4218.00	20	PolyTank Co.
Mineralization Tank	Diameter: 24, Depth: 48, Capacity=80 Gal	12	p	246.1	2953.20	20	PolyTank Co.
Communal / Degassing Tank	Diameter: 22, Depth: 30, Capacity=52 Gal	6	p	154.7	928.20	20	PolyTank Co.
Rockwool Grow Cubes	1" cubes, sheet of 200, for seeds germination	24	p	14.95	358.80	0.125	Nelson & Pade Inc.
Raft Trays	Rectangular, L32 , W32, D35, Capacity=135	24	p	365.6	8774.40	3	PolyTank Co.
Sump Tank	Diameter: 18, Depth: 24, Capacity=25 Gal	6	p	84.4	506.40	20	PolyTank Co.
Water Pump	Walchem Mag-Drive 20RLXT-115	6	p	185.95	1115.70	7	Nelson & Pade Inc.
Air Pump	Medo LA-45C	12	p	280.95	3371.40	7	Nelson & Pade Inc.
Inline Heater/Chiller	2kw Inline Water Heater, Stainless Steel	6	p	920	5520.00	7	Nelson & Pade Inc.

Light Bulb	Sun System Digital Grow Light (250 & 400 watt)	24	p	234.95	5638.80	1	Nelson & Pade Inc.
light Fixture	Metal Halide Grow Light Package	24	p	309.95	7438.80	10	Nelson & Pade Inc.
Water	One time annual fill, 3% daily loss compensation	427.188	m3/Year	1.28	239.19	N/A	Madison Water Utility

Table C54. Aquaponics production revenues.

Item	Item Specifications	Quantity (kg)	Unit	Unit Price ($US per kg)	Total Price ($US)	Comments / References
Tilapia	Live-weight product	555.871	kg/year	$17.76	$6,114.59	https://products.wholefoodsmarket.com
Hybrid Walleye	Live-weight product	284.669	kg/year	$44.00	$8,554.30	https://www.walleyedirect.com
Conventional Walleye	Live-weight product	350.640	kg/year	$44.00	$10,813.75	https://www.walleyedirect.com
Butterhead (2015)	Total weight	12.97	kg/year	31.42	407.51	https://www.foodcoop.com/produce/ https://products.wholefoodsmarket.com
Romaine (2015)	Total weight	32.21	kg/year	31.42	1012.04	https://www.ers.usda.gov/data-products/fruit-and-vegetable-prices/fruit-and-vegetable-prices/#Vegetables https://products.wholefoodsmarket.com
Kale (2015)	Total weight	7.63	kg/year	7.75	59.13	https://www.ers.usda.gov/data-products/fruit-and-vegetable-prices/fruit-and-vegetable-prices/#Vegetables https://products.wholefoodsmarket.com
Pak Choi (2015)	Total weight	38.28	kg/year	5.53	211.69	https://www.mysupermarket.co.uk/tesco-price-comparison/Vegetables/Tesco_Pak_Choi_250g.html https://products.wholefoodsmarket.com
Butterhead (2016)	Total weight	167.54	kg/year	31.42	5264.11	https://www.foodcoop.com/produce/ https://products.wholefoodsmarket.com
Romaine (2016)	Total weight	219.40	kg/year	31.42	6893.55	https://www.ers.usda.gov/data-products/fruit-and-vegetable-prices/fruit-and-vegetable-prices/#Vegetables https://products.wholefoodsmarket.com
Kale (2016)	Total weight	74.54	kg/year	7.75	577.68	https://www.ers.usda.gov/data-products/fruit-and-vegetable-prices/fruit-and-vegetable-prices/#Vegetables https://products.wholefoodsmarket.com
Pak Choi (2016)	Total weight	376.43	kg/year	5.53	2081.65	https://www.mysupermarket.co.uk/tesco-price-comparison/Vegetables/Tesco_Pak_Choi_250g.html https://products.wholefoodsmarket.com
Butterhead (2017)	Total weight	227.44	kg/year	31.42	7146.17	https://www.foodcoop.com/produce/ https://products.wholefoodsmarket.com

Romaine (2017)	Total weight	310.207	kg/year	31.42	9746.70	https://www.ers.usda.gov/data-products/fruit-and-vegetable-prices/fruit-and-vegetable-prices/#Vegetables https://products.wholefoodsmarket.com
Kale (2017)	Total weight	212.15	kg/year	7.75	1644.16	https://www.ers.usda.gov/data-products/fruit-and-vegetable-prices/fruit-and-vegetable-prices/#Vegetables https://products.wholefoodsmarket.com
Pak Choi (2017)	Total weight	415.85	kg/year	5.53	2299.65	https://www.mysupermarket.co.uk/tesco-price-comparison/Vegetables/Tesco_Pak_Choi_250g.html https://products.wholefoodsmarket.com

Table C55. Aquaponics operating costs based on 2015 data: tilapia production.

Item	Item Specifications	Quantity	Unit	Unit Price	Total Price	Comments / References
Heat	Utility unit price = 10 cents / kWh	24907	kWh/Year	0.10	2490.73	2015 Average annual Temperature = 8 °C
Electricity		5370	kWh/Year	0.15	805.50	
Seeds	12.50$ per ounces of seed	0.046	kg/Year	441.69	20.32	Deluxe Variety Premium Vegetable & Herb Garden 100% Non-GMO Heirloom
Aquafeed	Rangen tilapia (44-50 % crude protein)	1376	kg/Year	3.24	445.82	
Fingerlings	1-inch fingerlings	127	kg/Year	0.10	12.70	Quagrainie et al., 2017
Labor	1 individual, feeding: 1 hr / week, harvesting: 3 hr/week, maintenance: 1 hr/week	270	Hour/Year	10.00	2700.00	

Table C56. Aquaponics operating costs based on 2016 data: conventional walleye production.

Item	Item Specifications	Quantity	Unit	Unit Price	Total Price	Comments / References
Heat	Utility unit price = 10 cents / kWh	31885	kWh/Year	0.1	3188.48	2016 Average annual Temperature = 9 °C
Electricity		6658	kWh/Year	0.15	998.63	
Seeds	12.50$ per ounces of seed	0.046	kg/Year	441.69	20.32	Deluxe Variety Premium Vegetable & Herb Garden 100% Non-GMO Heirloom

Aquafeed	Skretting walleye (50-60% crude protein)	1899	kg/Year	6.8	1291.3	
Fingerlings	1-inch fingerlings	129	kg/Year	0.33	42.57	https://www.fishandboat.com/Fish/PennsylvaniaFishes/Documents/weightlength1.pdf http://www.watersmeettrouthatchery.com/stocking-prices.htm
Labor	1 individual, feeding: 1 hr / week, harvesting: 3 hr/week, maintenance: 1 hr/week	270	Hour/Year	10.00	2700	

Table C57. Aquaponics operating costs based on 2017 data: hybrid walleye (aka saugeye) production

Item	Item Specifications	Quantity	Unit	Unit Price	Total Price	Comments / References
Heat	Utility unit price = 10 cents / kWh	36610	kWh/Year	0.1	3661.03	2017 Average annual Temperature = 8 °C insideclimatenews.org
Electricity		8615	kWh/Year	0.15	1292.25	
Seeds	12.50$ per ounces of seed	0.046	kg/Year	441.69	20.32	Deluxe Variety Premium Vegetable & Herb Garden 100% Non-GMO Heirloom
Aquafeed	Skretting walleye (50-60% crude protein)	968	kg/Year	6.8	658.49	
Fingerlings	1-inch fingerlings	129	kg/Year	0.36	46.44	https://www.fishandboat.com/Fish/PennsylvaniaFishes/Documents/weightlength1.pdf http://www.watersmeettrouthatchery.com/stocking-prices.htm
Labor	1 individual, feeding: 1 hr / week, harvesting: 3 hr/week, maintenance: 1 hr/week	270	Hour/Year	10	2700	

Table C58. Contribution analysis results based on net present costs and revenues (i=10%, t=20 yrs.).

Parameter \ Production	Tilapia (2015)	C-Walleye (2016)	H-Walleye (2017)
Infrastructure	$147,311.67	$147,311.67	$147,311.67
Heat	$21,204.98	$27,145.32	$31,168.41

Electricity	$6,857.67	$8,501.90	$11,001.65
Aquafeed	$3,795.51	$10,991.01	$5,606.01
Labor	$22,986.62	$22,986.62	$22,986.62
Other operating costs	$4,936.33	$5,190.63	$5,223.58
Fish Revenue	-$83,916.49	-$131,348.62	-$106,636.47
Plants Revenue	-$14,391.07	-$126,145.38	-$284,030.87

Economic Analysis Methods

NPV

Net present value (NPV), as known as net present worth (NPW), accounts for the time value of money based on a set of periodic cash flows (typically 1-year periods) and an interest rate. NPV is calculated by the following formula:

$$\text{NPV}\ (i, N) = \sum_{t=1}^{N} \frac{\mathrm{R}t}{(1+i)^{t}} \qquad (1)$$

In which N is the total number of periods (e.g. 20 years), *i* is discount rate (e.g. 10%), and R*t* is the net cash flow at time t.

IRR

Internal rate of return (IRR) of an investment is the interest rate at which the net present value of costs (negative cash flows) of the investment equals the net present value of the benefits (positive cash flows) of the investment. Internal rates of return are commonly used to evaluate the comparative desirability of investments or projects with similar external conditions (e.g. inflation, risks, etc.). The higher a project's internal rate of return, the more financially desirable it is to undertake the project.

PBP

Payback period (PBP) is the amount of time (typically in years) to recover the initial investment in an opportunity. The payback period does not account for savings that may continue from a project after the initial investment is paid back from the profits of the project. However, this method is helpful for a first cut analysis of a project.

BCR

Benefit to cost ratio (BCR) is the ratio of the benefits of an investment (discounted value), expressed in monetary terms, relative to its costs (discounted value). As a general rule of thumb, the higher the BCR the better the investment. BCR is calculated by the following formula:

$$\text{BCR} = \frac{NPV\ (positive\ cash\ flows)}{-NPV(negative\ cash\ flows)} \qquad (2)$$

Table C59. Uncertainty analysis of environmental impacts based on 1 kg tilapia production (T, 2015).

Impact category	Unit	Mean	Median	SD	CV	2.5%	97.5%	SEM
Acidification	kg SO2 eq	0.142921	0.142909	0.00022	0.1541	0.142521	0.143355	6.96E-06
Carcinogenics	CTUh	1.61E-07	1.59E-07	1.34E-08	8.308363	1.44E-07	1.94E-07	4.24E-10
Ecotoxicity	CTUe	33.42039	32.84567	2.399508	7.179771	31.35234	38.81088	0.075879
Eutrophication	kg N eq	0.022946	0.022725	0.000986	4.298557	0.02221	0.025041	3.12E-05
Fossil fuel depletion	MJ surplus	34.46862	34.46342	0.10029	0.290961	34.28204	34.68094	0.003171
Global warming	kg CO2 eq	20.27215	20.27117	0.034344	0.169412	20.20317	20.34165	0.001086
Non carcinogenics	CTUh	5.42E-06	5.22E-06	6.73E-07	12.4017	4.77E-06	7.33E-06	2.13E-08
Ozone depletion	kg CFC-11 eq	9.93E-08	9.85E-08	6.12E-09	6.167772	8.98E-08	1.14E-07	1.94E-10
Respiratory effects	kg PM2.5 eq	0.008111	0.008109	2.34E-05	0.288078	0.008071	0.00816	7.39E-07
Smog	kg O3 eq	0.73065	0.730451	0.005096	0.697421	0.721046	0.741078	0.000161

* Monte Carlo Criterion: fixed number of runs = 1000, Confidence Interval = 95%.

Table C60. Uncertainty analysis of environmental impacts based on 1 kg conventional walleye production (C, 2016).

Impact category	Unit	Mean	Median	SD	CV	2.5%	97.5%	SEM
Acidification	kg SO2 eq	0.097867	0.097859	0.000114	0.116196	0.097659	0.098109	3.6E-06
Carcinogenics	CTUh	8.91E-08	8.7E-08	1.02E-08	11.46987	7.8E-08	1.17E-07	3.23E-10
Ecotoxicity	CTUe	17.84182	17.33589	2.46569	13.81972	16.20326	22.59564	0.077972

Eutrophication	kg N eq	0.008105	0.007513	0.00955	117.8367	0.007217	0.01009	0.000302
Fossil fuel depletion	MJ surplus	24.86191	24.86014	0.048915	0.196745	24.76835	24.96663	0.001547
Global warming	kg CO2 eq	13.78322	13.78312	0.01722	0.124936	13.75123	13.82118	0.000545
Non carcinogenics	CTUh	2.04E-06	1.9E-06	5.03E-07	24.62662	1.65E-06	3.38E-06	1.59E-08
Ozone depletion	kg CFC-11 eq	6.1E-08	6.04E-08	3.44E-09	5.645642	5.56E-08	6.99E-08	1.09E-10
Respiratory effects	kg PM2.5 eq	0.005721	0.00572	1.2E-05	0.209904	0.005699	0.005748	3.8E-07
Smog	kg O3 eq	0.635367	0.635103	0.002818	0.443449	0.63034	0.641598	8.91E-05

* Monte Carlo Criterion: fixed number of runs = 1000, Confidence Interval = 95%.

Table C61. Uncertainty analysis of environmental impacts based on 1 kg hybrid walleye production (H, 2017).

Impact category	Unit	Mean	Median	SD	CV	2.5%	97.5%	SEM
Acidification	kg SO2 eq	0.090268	0.090264	5.49E-05	0.060842	0.090171	0.09038	1.74E-06
Carcinogenics	CTUh	6.55E-08	6.42E-08	6.63E-09	10.11845	5.77E-08	8.17E-08	2.1E-10
Ecotoxicity	CTUe	14.13443	13.93621	1.380905	9.769794	13.26929	15.99524	0.043668
Eutrophication	kg N eq	0.003986	0.003875	0.000624	15.66567	0.003693	0.004889	1.97E-05
Fossil fuel depletion	MJ surplus	22.24493	22.24372	0.020865	0.093796	22.20809	22.29044	0.00066
Global warming	kg CO2 eq	11.67433	11.67376	0.008933	0.076518	11.65776	11.69271	0.000282
Non carcinogenics	CTUh	1.33E-06	1.23E-06	3.66E-07	27.45387	1.01E-06	2.31E-06	1.16E-08
Ozone depletion	kg CFC-11 eq	3.05E-08	3.01E-08	2.19E-09	7.162397	2.72E-08	3.58E-08	6.91E-11
Respiratory effects	kg PM2.5 eq	0.005206	0.005205	8.94E-06	0.171775	0.00519	0.005225	2.83E-07
Smog	kg O3 eq	0.493709	0.493632	0.001104	0.223513	0.491791	0.496057	3.49E-05

* Monte Carlo Criterion: fixed number of runs = 1000, Confidence Interval = 95%.

Table C62. Sensitivity Factors (SFs) for tilapia (T, 2015) production.

Impact category	Seeds	Aquafeed	Infrastructure	Electricity	Heat	Solids Waste
OD	8.04E-07	0.722811	0.240066	0.00225	6.42E-05	0.034807
GW	5.87E-07	0.240849	0.024917	0.295456	0.436797	0.001981
PS	1.89E-07	0.214458	0.030023	0.488517	0.262668	0.004334
AC	1.67E-06	0.104294	0.01674	0.34543	0.530138	0.003396
EU	2.16E-05	0.880139	0.036784	0.029172	0.032275	0.021608

HHC	2.17E-06	0.407794	0.209872	0.109782	0.228091	0.044459
HHNC	3.55E-05	0.699067	0.160734	0.045332	0.088647	0.006185
RE	1.05E-06	0.082666	0.046552	0.316552	0.55119	0.00304
EC	5.94E-06	0.386163	0.082096	0.128805	0.355035	0.047894
FF	1.11E-07	0.075969	0.040442	0.209367	0.673302	0.00092

Table C63. Sensitivity Factors (SFs) for C-walleye (C, 2016) production.

Impact category	Seeds	Aquafeed	Infrastructure	Electricity	Heat	Solids Waste
OD	8.04E-07	0.722811	0.240066	0.00225	6.42E-05	0.034807
GW	5.87E-07	0.240849	0.024917	0.295456	0.436797	0.001981
PS	1.89E-07	0.214458	0.030023	0.488517	0.262668	0.004334
AC	1.67E-06	0.104294	0.01674	0.34543	0.530138	0.003396
EU	2.16E-05	0.880139	0.036784	0.029172	0.032275	0.021608
HHC	2.17E-06	0.407794	0.209872	0.109782	0.228091	0.044459
HHNC	3.55E-05	0.699067	0.160734	0.045332	0.088647	0.006185
RE	1.05E-06	0.082666	0.046552	0.316552	0.55119	0.00304
EC	5.94E-06	0.386163	0.082096	0.128805	0.355035	0.047894
FF	1.11E-07	0.075969	0.040442	0.209367	0.673302	0.00092

Table C64. Sensitivity Factors (SFs) for H-walleye (H, 2017) production.

Impact category	Seeds	Aquafeed	Infrastructure	Electricity	Heat	Solids Waste
OD	8.04E-07	0.722811	0.240066	0.00225	6.42E-05	0.034807
GW	5.87E-07	0.240849	0.024917	0.295456	0.436797	0.001981
PS	1.89E-07	0.214458	0.030023	0.488517	0.262668	0.004334
AC	1.67E-06	0.104294	0.01674	0.34543	0.530138	0.003396
EU	2.16E-05	0.880139	0.036784	0.029172	0.032275	0.021608
HHC	2.17E-06	0.407794	0.209872	0.109782	0.228091	0.044459
HHNC	3.55E-05	0.699067	0.160734	0.045332	0.088647	0.006185
RE	1.05E-06	0.082666	0.046552	0.316552	0.55119	0.00304
EC	5.94E-06	0.386163	0.082096	0.128805	0.355035	0.047894
FF	1.11E-07	0.075969	0.040442	0.209367	0.673302	0.00092

Appendix D

Supplementary Information (SI) for chapter 6.

Table D65. Diet formulation inventory for FMOC-1.

	Section	Material	Amount	Unit	Reference
1 kg FMOC-1	Input	Poultry Meal	160	g	(John Davidson et al., 2016)
		Wheat Flour	195.1	g	
		Menhaden Meal	195	g	
		Fish Oil (whitefish Trimming oil)	0	g	
		Fish Oil (menhaden)	157.4	g	
		Soy Protein Concentrate	128.5	g	
		Blood Meal	70.5	g	
		Canola Oil	56.5	g	
		Corn Protein Concentrate	0	g	
		Dicalcium phosphate	5	g	
		Vitamin Premixg	10	g	
		Lysine-HCL	6.5	g	
		Choline CL	6	g	
		Taurine	0	g	
		DL-Methionine	4	g	

		Stay-C	2	g	
		Threonine	1.5	g	
		Trace Minerals Premix	1	g	
		Astaxanthin (Dye)	1	g	

Table D66. Diet formulation inventory for FMOC-2.

	Section	Material	Amount	Unit	Reference
1 kg FMOC-2	Input	Fish meal	250	g	(Carter et al., 2003)
		Soybean meal	56.2	g	
		Casein	143.2	g	
		Wheat Gluten	100	g	
		Canola oil	78.2	g	
		Fish oil	91.4	g	
		Thraustochytrid meal	0	g	
		Pregelatinized starch	136.2	g	
		Vitamin mix	3	g	
		Stay C	3	g	
		Choline CL	2	g	
		Mineral mix	5	g	
		Calsium phosphate	21.8	g	
		Cellulose	50	g	
		Bentonite	49	g	
		CMC (Carboxymethyl Cellulose)	9	g	
		Cholestane	1	g	

		Yttrium oxide	1	g	

* N/A: Not Applicable

Table D67. Input materials and energy required to produce Thraustochytrid meal.

	Section	Material	Amount	Unit	Reference
100 gr Thraustochytrid meal	Input (meal production)	Glucose	155	g	(Byreddy, 2015)
		Electricity	47.52	MJ	
		Electricity	5.28	MJ	
	Input (lipid extraction)	Methanol	1584	g	
		Chloroform	5960	g	

Table D68. Diet formulation inventory for FMOC-3.

	Section	Material	Amount	Unit	Reference
1 kg FMOC-3	Input	Fish meal	108	g	(Akiyama, 1990)
		Soybean meal	450	g	
		Wheat pollards	126	g	
		Rice bran	200	g	
		Dicalcium phosphate	46	g	
		Fish oil	18	g	
		Methionine	2	g	
		Limestone	24	g	
		Vitamin/Mineral premix	26	g	

	Section	Material	Amount	Unit	Reference

1 kg FMOC-4	Input	Soy protein concentrate	190	g	(Aas et al., 2019)
		Wheat gluten	90	g	
		Corn gluten	36	g	
		Vegetable protein (other resources)	86	g	
		Rapeseed oil	201	g	
		Wheat starch	89	g	
		marine protein, forage	117	g	
		marine protein, trimming	28	g	
		fish oil, forage	78	g	
		fish oil, trimming	26	g	
		Vitamins, minerals, amino acids, etc.	40	g	

Table D69. Diet formulation inventory for FMF-1-T.

	Section	Material	Amount	Unit	Reference
1 kg FMF-1-T	Input	Menhaden meal	0	g	(Rossi Jr & Davis, 2012)
		Poultry meal	147	g	
		Soybean meal	500	g	

		Menhaden oil	51.5	g	
		Corn starch	53.8	g	
		Whole wheat	160	g	
		Corn gluten meal	50	g	
		Lecithin	10	g	
		Mineral premix	2.5	g	
		Vitamin premix	5	g	
		Choline Cl	2	g	
		Stay C	1	g	
		CaPO4	16	g	
		Dl-methionine	1.2	g	

Table D70. Diet formulation inventory for FMF-2-T.

	Section	Material	Amount	Unit	Reference
1 kg FMF-2-T	Input	Blood meal	300	g	(El - Sayed, 1998)
		Wheat bran	460	g	
		Corn starch	100	g	
		Sardine oil	15	g	
		Soybean oil	15	g	
		Vitamin mix	10	g	
		Mineral mix	10	g	
		Monocalcium phosphate	20	g	
		Alpha cellulose	70	g	

Table D71. Diet formulation inventory for FMF-3-P.

	Section	Material	Amount	Unit	Reference
1 kg FMF-3-P	Input	Corn gluten meal (CGM)	360	g	(Adelizi et al., 1998)
		Yellow corn	152	g	
		Corn gluten feed	125	g	
		Peanut meal	204	g	
		Soybean oil	7	g	
		Menhadden oil	95	g	
		Lysine	10.2	g	
		Methionine	1.7	g	
		Dicalcium phosphate	32.7	g	
		Vitamin premix	3	g	
		Mineral premix	1.5	g	
		Vitamin C	1	g	
		Choline Cl	7	g	

Table D72. Diet formulation inventory for FMF-4-P.

	Section	Material	Amount	Unit	Reference
1 kg FMF-3-P	Input	Corn gluten meal (CGM)	227	g	(Adelizi et al., 1998)
		Yellow corn	184	g	
		Corn gluten feed	32	g	
		Soybean meal	403	g	
		Soybean oil	7	g	

		Menhadden oil	95	g	
		Lysine	1.3	g	
		Methionine	2.4	g	
		Dicalcium phosphate	35.6	g	
		Vitamin premix	3	g	
		Mineral premix	1.5	g	
		Vitamin C	1	g	
		Choline Cl	7	g	

Table D73. Diet formulation inventory for FMF-5-S.

	Section	Material	Amount	Unit	Reference
1 kg FMF-5-S	Input	Alaskan pollock fish meal	152.95	g	(Ian Forster et al., 2004)
		Menhaden oil	29	g	
		Wheat starch	13.85	g	
		Whole wheat flour	555	g	
		Vital wheat gluten	40	g	
		Brewer’s yeast	50	g	
		Squid liver powder	25	g	
		Soybean meal	90	g	
		Soy lecithin	20	g	
		Cholesterol	2.4	g	

		Vitamin premix	4	g	
		Choline Cl	1.2	g	
		Vitamin C	0.8	g	
		Phosphate minerals (as Sodium)	16.8	g	

* N/S: Not Specified

Table D74. Diet formulation inventory for FOF-1.

	Section	Material	Amount	Unit	Reference
1 kg FOF-1	Input	Fish meal	250	g	(Carter et al., 2003)
		Soybean meal	56.2	g	
		Casein	143.2	g	
		Wheat Gluten	100	g	
		Canola oil	169.6	g	
		Fish oil	0	g	
		Thraustochytrid meal	0	g	
		Pregelatinized starch	150	g	
		Vitamin mix	3	g	
		Stay C	3	g	
		Choline CL	2	g	
		Mineral mix	5	g	
		Calsium phosphate	21.8	g	
		Cellulose	36.2	g	
		Bentonite	49	g	
		CMC (Carboxymethyl Cellulose)	9	g	

		Cholestane	1	g	
		Yttrium oxide	1	g	

* N/A: Not Applicable

Table D75. Diet formulation inventory for FOF-2.

	Section	Material	Amount	Unit	Reference
1 kg FOF-2	Input	Fish meal	250	g	(Carter et al., 2003)
		Soybean meal	36.5	g	
		Casein	132.9	g	
		Wheat Gluten	100	g	
		Canola oil	110.5	g	
		Fish oil	0	g	
		Thraustochytrid meal	100	g	
		Pregelatinized starch	150	g	
		Vitamin mix	3	g	
		Stay C	3	g	
		Choline CL	2	g	
		Mineral mix	5	g	
		Calsium phosphate	23	g	
		Cellulose	24.2	g	
		Bentonite	49	g	
		CMC (Carboxymethyl Cellulose)	9	g	
		Cholestane	1	g	
		Yttrium oxide	1	g	

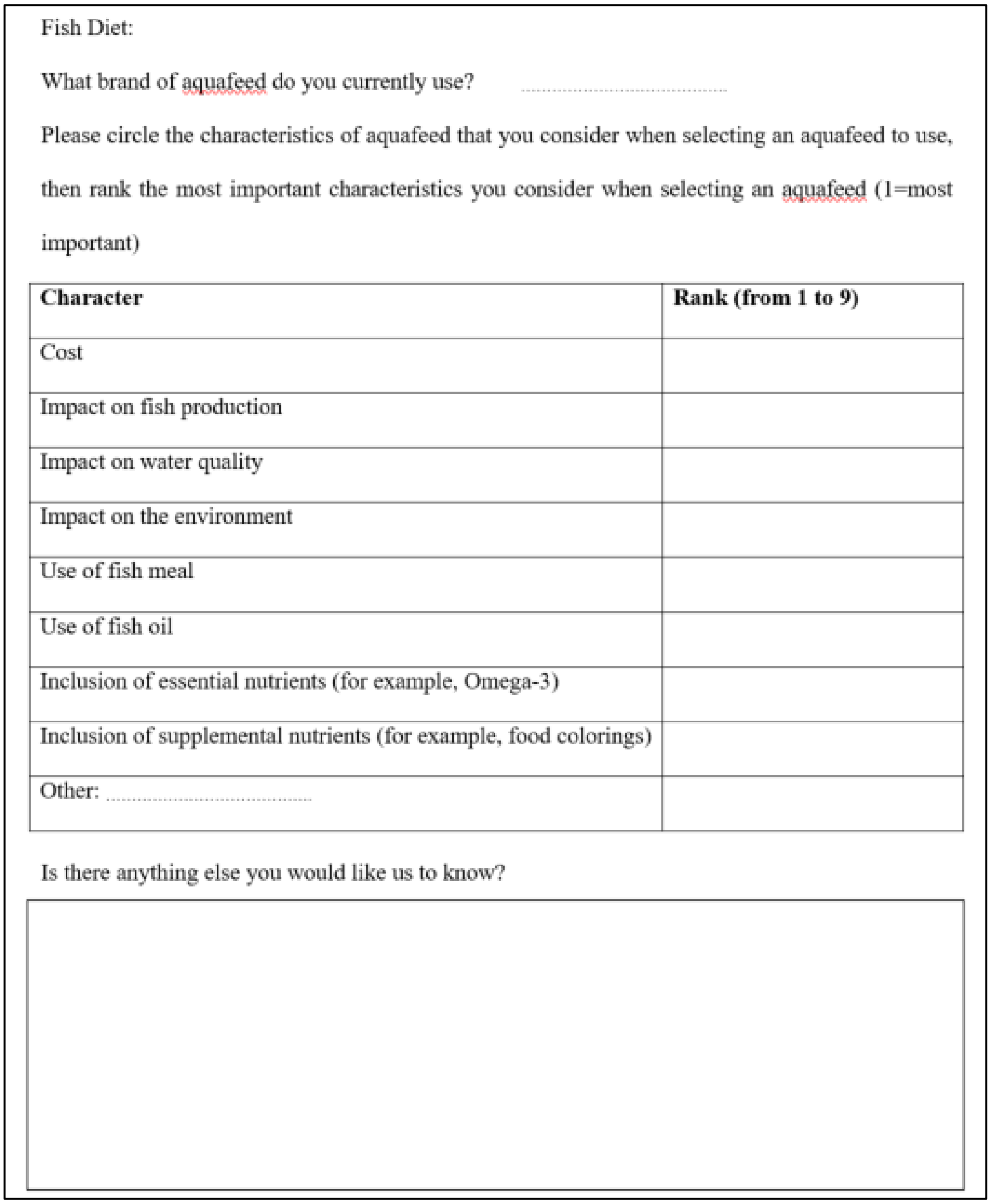
* N/A: Not Applicable

Table D76. Diet formulation inventory for FMOF.

	Section	Material	Amount	Unit	Reference
1 kg FMOF	Input	Mixed Nut Meal	320	g	(John Davidson et al., 2016)
		Poultry Meal	295	g	
		Wheat Flour	99.4	g	
		Menhaden Meal	0	g	
		Fish Oil (whitefish Trimming oil)	182	g	
		Fish Oil (menhaden)	0	g	
		Soy Protein Concentrate	0	g	
		Blood Meal	0	g	
		Canola Oil	0	g	
		Corn Protein Concentrate	35.6	g	
		Dicalcium phosphate	32.5	g	
		Vitamin Premixg	10	g	
		Lysine-HCL	6.2	g	
		Choline CL	6	g	
		Taurine	5	g	
		DL-Methionine	2.8	g	
		Stay-C	3	g	
		Threonine	0.5	g	
		Trace Minerals Premix	1	g	

		Astaxanthin (Dye)	1	g	

Table D77. Survey form for characteristics ranking assignment by the Wisconsin aquafarmers.



Fish Diet:

What brand of aquafeed do you currently use? ....

Please circle the characteristics of aquafeed that you consider when selecting an aquafeed to use, then rank the most important characteristics you consider when selecting an aquafeed (1=most important)

Character	**Rank (from 1 to 9)**
Cost	
Impact on fish production	
Impact on water quality	
Impact on the environment	
Use of fish meal	
Use of fish oil	
Inclusion of essential nutrients (for example, Omega-3)	
Inclusion of supplemental nutrients (for example, food colorings)	
Other:	

Is there anything else you would like us to know?

Table D78. Summary of the decision characteristics rankings and associated ROC weightings using survey results from fish farmers.

Characteristic	Cost		Impact on Fish Production		Impact on Water Quality		Impact on the Environment		Use of Fish Meal		Use of Fish Oil		Inclusion of Essential Nutrients		Inclusion of Supplemental Nutrients	
Score	Rank	Priority Weight	Rank	Priority Weight	Rank	Priority Weight	Rank	Priority Weight	Rank	Priority Weight	Rank	Priority Weight	Rank	Priority Weight	Rank	Priority Weight
Farmer A	7	0.033	8	0.016	1	0.340	2	0.215	6	0.054	5	0.079	3	0.152	4	0.111
Farmer B	3	0.152	2	0.215	1	0.340	1	0.340	4	0.111	5	0.079	6	0.054	NC*	0.000
Farmer C	4	0.111	1	0.340	2	0.215	3	0.152	6	0.054	7	0.033	5	0.079	8	0.016
Farmer D	3	0.152	1	0.340	5	0.079	NC*	0.000	2	0.215	NC*	0.000	4	0.111	NC*	0.000
Farmer E	4	0.111	NC*	0.000	3	0.152	7	0.033	5	0.079	6	0.054	1	0.340	2	0.215
Farmer F	1	0.340	5	0.079	3	0.152	2	0.215	6	0.054	7	0.033	4	0.111	8	0.016
Farmer G	6	0.054	2	0.215	3	0.152	4	0.111	1	0.340	8	0.016	5	0.079	7	0.033
Farmer H	1	0.340	2	0.215	3	0.152	8	0.016	6	0.054	5	0.079	4	0.111	7	0.033

*NC: Not Covered

Table D79. Aquafeeds Cost attribution Based on the including Ingredients.

FMOC-1 (John Davidson et al., 2016)			
Ingredient	g/kg	ingredient price estimate ($/g)	Price attribution Source
Mixed Nut Meal	0	0.00141	FAO Database
Poultry Meal	160	0.001	FAO Database
Wheat Flour	195.1	0.00022	FAO Database
Menhaden Meal	195	0.00142	FAO Database
Fish Oil (whitefish Trimming oil)	0	0	FAO Database
Fish Oil (menhaden)	157.4	0.00185	FAO Database
Soy Protein Concentrate	128.5	0.0012	Online Search
Blood Meal	70.5	0.000587	Online Search
Canola Oil	56.5	0.00086	FAO Database
Corn Protein Concentrate	0	0.00081	Online Search
Dicalcium phosphate	5	0.00093	Online Search
Vitamin Premix	10	0.02989	Online Search
Lysine-HCL	6.5	0.0012	Online Search
Choline CL	6	0.0009	Online Search
Taurine	0	0.023	Online Search

DL-Methionine	4	0.113	Online Search
Stay-C	2	0.012	Online Search
Threonine	1.5	0.0011	Online Search
Trace Minerals Premix	1	0.0794	Online Search
Astaxanthin (Dye)	1	2.25	Online Search
Total Ingredient-Based Price ($/kg)	4.139		
FMOC-2 (Carter et al., 2003)			
Ingredient	g/kg	ingredient price ($/g)	Price attribution Source
Fish meal	250	0.00142	FAO Database
Soybean meal	56.2	0.00033	FAO Database
Casein	143.2	0.0155	Online Search
Wheat Gluten	100	0.0014	Online Search
Canola oil	78.2	0.00086	FAO Database
Fish oil	91.4	0.00185	FAO Database
Thraustochytrid meal	0	0.0489	Online Search
Pregelatinized starch	136.2	0.00085	Online Search
Vitamin mix	3	0.02989	Online Search
Stay C	3	0.012	Online Search
Choline CL	2	0.0009	Online Search
Mineral mix	5	0.0794	Online Search
Calsium phosphate	21.8	0.00093	Online Search
Cellulose	50	0.00275	Online Search
Bentonite	49	0.0001	Online Search
CMC (Carboxymethyl Cellulose)	9	0.012	Online Search
Cholestane	1	0.126	Online Search
Yttrium oxide	1	0.0031	Online Search
Total Ingredient-Based Price ($/kg)	4.006		
FMOC-3 (Akiyama, 1990)			
Ingredient	g/kg	ingredient price ($/g)	Price attribution Source
Fish meal	108	0.00142	FAO Database
Soybean meal	450	0.00033	FAO Database

Wheat pollards	126	0.00022	FAO Database
Rice bran	200	0.00085	FAO Database
Dicalcium phosphate	46	0.00093	Online Search
Fish oil	18	0.00185	FAO Database
Methionine	2	0.113	Online Search
Limestone	24	0.000035	Online Search
Vitamin/Mineral premix	26	0.02989	Online Search
Total Ingredient-Based Price ($/kg)	1.579		
FMOC-4 (Aas et al., 2019)			
Ingredient	g/kg	ingredient price ($/g)	Price attribution Source
Soy protein concentrate	190	0.0012	Online Search
Wheat gluten	90	0.0014	Online Search
Corn gluten	36	0.000415	Online Search
Vegetable protein (other resources)	86	0.002	Online Search
Rapeseed oil	201	0.00086	FAO Database
Wheat starch	89	0.00021	FAO Database
Pea starch and undefined plant carbohydrate	18	0.00085	Online Search
marine protein, forage	117	0.00142	FAO Database
marine protein, trimming	28	0	FAO Database
fish oil, forage	78	0.00185	FAO Database
fish oil, trimming	26	0	FAO Database
Vitamins, minerals, amino acids, etc.	40	0.000035	Online Search
Total Ingredient-Based Price ($/kg)	1.059		
FMF-1-T (Rossi Jr & Davis, 2012)			
Ingredient	g/kg	ingredient price ($/g)	Price attribution Source
Menhaden meal	0	0.00142	FAO Database
Poultry by-product meal	147	0.001	FAO Database
Soybean meal	500	0.00033	FAO Database
Menhaden oil	51.5	0.00185	FAO Database
Corn starch	53.8	0.00016	FAO Database
Whole wheat	160	0.00022	FAO Database

Corn gluten meal	50	0.0161	Online Search
Lecithin	10	0.015	Online Search
Mineral premix	2.5	0.0794	Online Search
Vitamin premix	5	0.02989	Online Search
Choline Cl	2	0.0009	Online Search
Stay C	1	0.012	Online Search
CaPO4	16	0.00093	Online Search
Dl-methionine	1.2	0.113	Online Search
Total Ingredient-Based Price ($/kg)	1.918		
FMF-2-T (El-Sayed, 1998)			
Ingredient	g/kg	ingredient price ($/g)	Price attribution Source
Blood meal	300	0.000587	Online Search
Wheat bran	460	0.000225	Online Search
Corn starch	100	0.00016	FAO Database
Sardine oil	15	0.00185	FAO Database
Soybean oil	15	0.00070848	Online Search
Vitamin mix	10	0.02989	Online Search
Mineral mix	10	0.0794	Online Search
Monocalcium phosphate	20	0.00093	Online Search
Alpha cellulose	70	0.00275	Online Search
Total Ingredient-Based Price ($/kg)	1.63		
FMF-3-P (Adelizi et al., 1998)			
Ingredient	g/kg	ingredient price ($/g)	Price attribution Source
Corn gluten meal	360	0.000415	Online Search
Yellow corn	152	0.00016	FAO Database
Corn gluten feed	125	0.00027	Online Search
Peanut meal	204	0.00076	Online Search
Soybean oil	7	0.000789	Online Search
Menhadden oil	95	0.00185	FAO Database
Lysine	10.2	0.0012	Online Search
Methionine	1.7	0.113	Online Search

Dicalcium phosphate	32.7	0.00093	Online Search
Vitamin premix	3	0.02989	Online Search
Mineral premix	1.5	0.0794	Online Search
Vitamin C	1	0.012	Online Search
Choline Cl	7	0.0009	Online Search
Total Ingredient-Based Price ($/kg)	1.0056		
FMF-4-P (Adelizi et al., 1998)			
Ingredient	g/kg	ingredient price ($/g)	Price attribution Source
Corn gluten meal	227	0.000415	Online Search
Yellow corn	184	0.00016	FAO Database
Corn gluten feed	32	0.00027	Online Search
Soybean meal	403	0.00033	FAO Database
Soybean oil	7	0.000789	Online Search
Menhaden oil	95	0.00185	FAO Database
Lysine	1.3	0.0012	Online Search
Methionine	2.4	0.113	Online Search
Dicalcium phosphate	35.6	0.00093	Online Search
Vitamin premix	3	0.02989	Online Search
Mineral premix	1.5	0.0794	Online Search
Vitamin C	1	0.012	Online Search
Choline Cl	7	0.0009	Online Search
Total Ingredient-Based Price ($/kg)	0.979		
FMF-5-S (Ian Forster et al., 2004)			
Ingredient	g/kg	ingredient price ($/g)	Price attribution Source
Alaskan pollock fish meal	152.95	0	FAO Database
Menhaden oil	29	0.00185	FAO Database
Wheat starch	13.85	0.00021	FAO Database
Whole wheat flour	555	0.00022	FAO Database
Vital wheat gluten	40	0.0014	Online Search
Brewers yeast	50	0.000625	Online Search
Squid liver powder	25	0.000492	Online Search

Soybean meal	90	0.00033	FAO Database
Soy lecithin	20	0.015	Online Search
Cholesterol	2.4	0.126	Online Search
Vitamin premix	4	0.012	Online Search
Choline Cl	1.2	0.0009	Online Search
Vitamin C	0.8	0.0009	Online Search
Phosphate minerals (as Sodium)	16.8	0.0009	Online Search
Total Ingredient-Based Price ($/kg)	0.975		
FOF-1 (Carter et al., 2003)			
Ingredient	g/kg	ingredient price ($/g)	Price attribution Source
Fish meal	250	0.00142	FAO Database
Soybean meal	56.2	0.00033	FAO Database
Casein	143.2	0.0155	Online Search
Wheat Gluten	100	0.0014	Online Search
Canola oil	169.6	0.00086	FAO Database
Fish oil	0	0.00185	FAO Database
Thraustochytrid meal	0	0.0489	Online Search
Pregelatinized starch	150	0.00085	Online Search
Vitamin mix	3	0.02989	Online Search
Stay C	3	0.012	Online Search
Choline CL	2	0.0009	Online Search
Mineral mix	5	0.0794	Online Search
Calsium phosphate	21.8	0.00093	Online Search
Cellulose	36.2	0.00275	Online Search
Bentonite	49	0.0001	Online Search
CMC (Carboxymethyl Cellulose)	9	0.012	Online Search
Cholestane	1	0.126	Online Search
Yttrium oxide	1	0.0031	Online Search
Total Ingredient-Based Price ($/kg)	3.893		
FOF-2 (Carter et al., 2003)			
Ingredient	g/kg	ingredient price ($/g)	Price attribution Source

Fish meal	250	0.00142	FAO Database
Soybean meal	36.5	0.00033	FAO Database
Casein	132.9	0.0155	Online Search
Wheat Gluten	100	0.0014	Online Search
Canola oil	110.5	0.00086	FAO Database
Fish oil	0	0.00185	FAO Database
Thraustochytrid oil	100	0.0489	Online Search
Pregelatinized starch	150	0.00085	Online Search
Vitamin mix	3	0.02989	Online Search
Stay C	3	0.012	Online Search
Choline Cl	2	0.0009	Online Search
Mineral mix	5	0.0794	Online Search
Calsium phosphate	23	0.00093	Online Search
Cellulose	24.2	0.00275	Online Search
Bentonite	49	0.0001	Online Search
CMC (Carboxymethyl Cellulose)	9	0.012	Online Search
Cholestane	1	0.126	Online Search
Yttrium oxide	1	0.0031	Online Search
Total Ingredient-Based Price ($/kg)	8.534		

FMOF (John Davidson et al., 2016)

Ingredient	g/kg	ingredient price ($/g)	Price attribution Source
Mixed Nut Meal	320	0.00141	FAO Database
Poultry Meal	295	0.001	FAO Database
Wheat Flour	99.4	0.00022	FAO Database
Menhaden Meal	0	0.00142	FAO Database
Fish Oil (whitefish Trimming oil)	182	0	FAO Database
Fish Oil (menhaden)	0	0.00185	FAO Database
Soy Protein Concentrate	0	0.0012	Online Search
Blood Meal	0	0.000587	Online Search
Canola Oil	0	0.00086	FAO Database
Corn Protein Concentrate	35.6	0.00081	Online Search

Dicalcium phosphate	32.5	0.00093	Online Search
Vitamin Premix	10	0.02989	Online Search
Lysine-HCL	6.2	0.0012	Online Search
Choline CL	6	0.0009	Online Search
Taurine	5	0.023	Online Search
DL-Methionine	2.8	0.113	Online Search
Stay-C	3	0.012	Online Search
Threonine	0.5	0.0011	Online Search
Trace Minerals Premix	1	0.0794	Online Search
Astaxanthin	1	2.25	Online Search
Total Ingredient-Based Price ($/kg)	3.936		

Table D80. The attributed aquafeeds characteristics for FCR, Protein Content, and Vitamin C.

Aquafeed	FCR	Protein (Pr%)	Supplemental Vitamin C (g/kg)
FMOC-1	0.9	42.3	2
FMOC-2	0.86	41	3
FMOC-3	2.1	30.1	0
FMOC-4	1.21	35.6	0
FMF-1-T	2.5	38.5	1
FMF-2-T	2.6	30.8	0
FMF-3-P	1.21	39.9	1
FMF-4-P	1.25	38.5	1
FMF-5-S	1.33	34	0.8
FOF-1	0.84	39.8	3
FOF-2	0.91	39.1	3
FMOF	0.89	42.2	3

Data from: Ghamkhar and Hicks (2020).

Table D81. Ingredient-based Digestible Energy Calculations for Aquafeeds(C. Cho & Kaushik, 1990)

FMOC-1		
Ingredient	g/kg	DE (MJ/g)
Mixed Nut Meal	0	0.0081
Poultry Meal	160	0.0139
Wheat Flour	195.1	0.0076
Menhaden Meal	195	0.0188
Fish Oil (whitefish Trimming oil)	0	0.0172
Fish Oil (menhaden)	157.4	0.0172
Soy Protein Concentrate	128.5	0.0154
Blood Meal	70.5	0.0194
Canola Oil	56.5	0.01086
Corn Protein Concentrate	0	0.0107
Dicalcium phosphate	5	N/S*
Vitamin Premix	10	N/S*
Lysine-HCL	6.5	N/S*
Choline CL	6	N/S*
Taurine	0	N/S*
DL-Methionine	4	0.0134
Stay-C	2	N/S*
Threonine	1.5	N/S*
Trace Minerals Premix	1	N/S*
Astaxanthin (Dye)	1	N/S*
Overall DE (MJ/kg)	14.09	
FMOC-2		
Ingredient	g/kg	DE (MJ/g)
Fish meal	250	0.0188
Soybean meal	56.2	0.0135
Casein	143.2	0.0154
Wheat Gluten	100	0.0076
Canola oil	78.2	0.01086

Fish oil	91.4	0.0172
Thraustochytrid meal	0	0.0077
Pregelatinized starch	136.2	0.0086
Vitamin mix	3	N/S*
Stay C	3	N/S*
Choline CL	2	N/S*
Mineral mix	5	N/S*
Calsium phosphate	21.8	N/S*
Cellulose	50	N/S*
Bentonite	49	N/S*
CMC (Carboxymethyl Cellulose)	9	N/S*
Cholestane	1	N/S*
Yttrium oxide	1	N/S*
Overall DE (MJ/kg)	12.01	
FMOC-3		
Ingredient	g/kg	DE (MJ/g)
Fish meal	108	0.0188
Soybean meal	450	0.0135
Wheat pollards	126	0.0076
Rice bran	200	0.0077
Dicalcium phosphate	46	N/S*
Fish oil	18	0.0172
Methionine	2	0.0134
Limestone	24	N/S*
Vitamin/Mineral premix	26	N/S*
Overall DE (MJ/kg)	10.94	
FMOC-4		
Ingredient	g/kg	DE (MJ/g)
Soy protein concentrate	190	0.0154
Wheat gluten	90	0.0076

Corn gluten	36	0.0176
Vegetable protein (other resources)	86	0.0081
Rapeseed oil	201	0.0081
Wheat starch	89	0.0133
Pea starch and undefined plant carbohydrate	18	0.0086
marine protein, forage	117	0.0188
marine protein, trimming	28	0.0188
fish oil, forage	78	0.0172
fish oil, trimming	26	0.0172
Vitamins, minerals, amino acids, etc.	40	N/S*
Overall DE (MJ/kg)	12.420	
FMF-1-T		
Ingredient	g/kg	DE (MJ/g)
Menhaden meal	0	0.0188
Poultry by-product meal	147	0.0139
Soybean meal	500	0.0135
Menhaden oil	51.5	0.0172
Corn starch	53.8	0.0066
Whole wheat	160	0.0076
Corn gluten meal	50	0.0176
Lecithin	10	N/S*
Mineral premix	2.5	N/S*
Vitamin premix	5	N/S*
Choline Cl	2	N/S*
Stay C	1	N/S*
CaPO4	16	N/S*
Dl-methionine	1.2	0.0134
Overall DE (MJ/kg)	12.15	
FMF-2-T		

Ingredient	g/kg	DE (MJ/g)
Blood meal	300	0.0194
Wheat bran	460	0.0076
Corn starch	100	0.0066
Sardine oil	15	0.0172
Soybean oil	15	0.019
Vitamin mix	10	N/S*
Mineral mix	10	N/S*
Monocalcium phosphate	20	N/S*
Alpha cellulose	70	N/S*
Total Ingredient-Based Price ($/kg)	10.52	
FMF-3-P		
Ingredient	g/kg	DE (MJ/g)
Corn gluten meal	360	0.0176
Yellow corn	152	0.0066
Corn gluten feed	125	0.0054
Peanut meal	204	0.0081
Soybean oil	7	0.019
Menhadden oil	95	0.0172
Lysine	10.2	N/S*
Methionine	1.7	0.0134
Dicalcium phosphate	32.7	N/S*
Vitamin premix	3	N/S*
Mineral premix	1.5	N/S*
Vitamin C	1	N/S*
Choline Cl	7	N/S*
Overall DE (MJ/kg)	11.46	
FMF-4-P		
Ingredient	g/kg	DE (MJ/g)
Corn gluten meal	227	0.0176

Yellow corn	184	0.0066
Corn gluten feed	32	0.0054
Soybean meal	403	0.0135
Soybean oil	7	0.019
Menhaden oil	95	0.0172
Lysine	1.3	N/S
Methionine	2.4	0.0134
Dicalcium phosphate	35.6	N/S*
Vitamin premix	3	N/S*
Mineral premix	1.5	N/S*
Vitamin C	1	N/S*
Choline Cl	7	N/S*
Overall DE (MJ/kg)	12.62	
FMF-5-S		
Ingredient	g/kg	DE (MJ/g)
Alaskan pollock fish meal	152.95	0.0188
Menhaden oil	29	0.0172
Wheat starch	13.85	0.0133
Whole wheat flour	555	0.0076
Vital wheat gluten	40	0.0076
Brewers yeast	50	0.0139
Squid liver powder	25	0.0109
Soybean meal	90	0.0135
Soy lecithin	20	N/S*
Cholesterol	2.4	N/S*
Vitamin premix	4	N/S*
Choline Cl	1.2	N/S*
Vitamin C	0.8	N/S*
Phosphate minerals (as Sodium)	16.8	N/S*
Overall DE (MJ/kg)	10.26	

FOF-1		
Ingredient	g/kg	DE (MJ/g)
Fish meal	250	0.0188
Soybean meal	56.2	0.0135
Casein	143.2	0.0134
Wheat Gluten	100	0.0076
Canola oil	169.6	0.01086
Fish oil	0	0.0172
Thraustochytrid meal	0	0.0077
Pregelatinized starch	150	0.0086
Vitamin mix	3	N/S*
Stay C	3	N/S*
Choline CL	2	N/S*
Mineral mix	5	N/S*
Calsium phosphate	21.8	N/S*
Cellulose	36.2	N/S*
Bentonite	49	N/S*
CMC (Carboxymethyl Cellulose)	9	N/S*
Cholestane	1	N/S*
Yttrium oxide	1	N/S*
Overall DE (MJ/kg)	11.27	
FOF-2		
Ingredient	g/kg	DE (MJ/g)
Fish meal	250	0.0188
Soybean meal	36.5	0.0135
Casein	132.9	0.0134
Wheat Gluten	100	0.0076
Canola oil	110.5	0.01086
Fish oil	0	0.0172
Thraustochytrid oil	100	0.0077

Pregelatinized starch	150	0.0086
Vitamin mix	3	N/S*
Stay C	3	N/S*
Choline Cl	2	N/S*
Mineral mix	5	N/S*
Calsium phosphate	23	N/S*
Cellulose	24.2	N/S*
Bentonite	49	N/S*
CMC (Carboxymethyl Cellulose)	9	N/S*
Cholestane	1	N/S*
Yttrium oxide	1	N/S*
Overall DE (MJ/kg)	10.99	
FMOF		
Ingredient	g/kg	DE (MJ/g)
Mixed Nut Meal	320	0.0081
Poultry Meal	295	0.0139
Wheat Flour	99.4	0.0076
Menhaden Meal	0	0.0188
Fish Oil (whitefish Trimming oil)	182	0.0172
Fish Oil (menhaden)	0	0.0172
Soy Protein Concentrate	0	0.0154
Blood Meal	0	0.0194
Canola Oil	0	0.01086
Corn Protein Concentrate	35.6	0.0107
Dicalcium phosphate	32.5	N/S*
Vitamin Premix	10	N/S*
Lysine-HCL	6.2	N/S*
Choline CL	6	N/S*
Taurine	5	N/S*
DL-Methionine	2.8	0.0134

Stay-C	3	N/S*
Threonine	0.5	N/S*
Trace Minerals Premix	1	N/S*
Astaxanthin	1	N/S*
Overall DE (MJ/kg)	10.99	

*N/S: Not Specified

Table D82. Environmental Impacts Quantities of Aquafeeds Based on Unit Mass (1 kg) Protein Provision.

Impact	GW	EU	WI	BRU
Unit	kg CO2-eq	kg N-eq	Liters	g C
FMOC-1	10.39206	0.048683	51.78214	199419.0733
FMOC-2	2.607145602	0.017319189	61.2195122	120390.0122
FMOC-3	11.94411	0.034031	155.2842	35744.82646
FMOC-4	7.911468	0.045185	119.0308	129406.0656
FMF-1-T	3.87701	0.020936	32.23319	73118.42747
FMF-2-T	26.6186	0.151659	211.794	34672.36156
FMF-3-P	3.126373	0.031827	158.0096	120870.259
FMF-4-P	1.755256	0.012191	38.44242	124898.5849
FMF-5-S	2.297752483	0.020291138	11.23529412	46027.71224
FOF-1	2.842072924	0.028233277	76.6165502	8969.403518
FOF-2	27.93617	0.030705	-80.3756	8936.787212
FMOF	6.961859072	0.039639927	395.3691833	85657.23697

Table D83. MCDA Results Based on Real-Case (Survey Based) Weighting Scenarios.

	Rank	action	Phi	Phi+	Phi-
Farmer A	1	FMOC-1	0.4549	0.7275	0.2725
	2	FMOC-2	0.3724	0.6661	0.2937
	3	FMF-4-P	0.3549	0.647	0.2921
	4	FOF-1	0.2467	0.5997	0.353
	5	FMF-1-T	0.1958	0.571	0.3753
	6	FMF-3-P	0.0464	0.4989	0.4525
	7	FMOC-4	0.0289	0.5036	0.4747

	8	FMOF	-0.0548	0.4321	0.487
	9	FOF-2	-0.0656	0.4281	0.4937
	10	FMF-5-S	-0.2531	0.3734	0.6266
	11	FMOC-3	-0.5206	0.2296	0.7502
	12	FMF-2-T	-0.8059	0.0771	0.883
Farmer B	Rank	action	Phi	Phi+	Phi-
	1	FOF-1	0.3521	0.6654	0.3134
	2	FMF-4-P	0.346	0.6527	0.3067
	3	FMOC-2	0.3075	0.6459	0.3384
	4	FMOC-1	0.2061	0.6031	0.3969
	5	FMOC-4	0.1291	0.557	0.4279
	6	FMF-1-T	0.0725	0.5187	0.4462
	7	FMF-5-S	0.0222	0.5111	0.4889
	8	FMF-3-P	0.0136	0.4808	0.4672
	9	FOF-2	-0.1256	0.4146	0.5402
	10	FMOF	-0.2181	0.3634	0.5814
	11	FMOC-3	-0.3429	0.3286	0.6714
	12	FMF-2-T	-0.7626	0.1031	0.8656
Farmer C	Rank	action	Phi	Phi+	Phi-
	1	FOF-1	0.4619	0.7224	0.2605
	2	FMOC-2	0.4167	0.7013	0.2845
	3	FMOC-1	0.3169	0.6585	0.3415
	4	FMF-4-P	0.2049	0.5861	0.3812
	5	FMOC-4	0.0951	0.5306	0.4355
	6	FMF-3-P	0.0608	0.5022	0.4414
	7	FMOF	0.0383	0.4974	0.4591
	8	FOF-2	-0.0496	0.4568	0.5065
	9	FMF-1-T	-0.147	0.4116	0.5586
	10	FMF-5-S	-0.1584	0.4208	0.5792
	11	FMOC-3	-0.4487	0.2742	0.7229
	12	FMF-2-T	-0.7909	0.0933	0.8842

Farmer D	Rank	action	Phi	Phi+	Phi-
	1	FOF-1	0.5547	0.7555	0.2009
	2	FMOC-2	0.5012	0.7288	0.2276
	3	FMOC-1	0.3544	0.6772	0.3228
	4	FOF-2	0.1093	0.5288	0.4196
	5	FMOC-4	0.0986	0.5321	0.4335
	6	FMOF	0.0809	0.4929	0.412
	7	FMF-3-P	0.0196	0.449	0.4294
	8	FMF-4-P	-0.0677	0.4169	0.4846
	9	FMF-5-S	-0.1043	0.4479	0.5521
	10	FMOC-3	-0.3966	0.3017	0.6983
	11	FMF-1-T	-0.4605	0.2205	0.6811
	12	FMF-2-T	-0.6895	0.1117	0.8012
Farmer E	Rank	action	Phi	Phi+	Phi-
	1	FMOC-1	0.5273	0.7637	0.2363
	2	FMOC-2	0.429	0.6774	0.2484
	3	FMOF	0.3105	0.6038	0.2933
	4	FOF-1	0.2516	0.5862	0.3346
	5	FMF-3-P	0.1827	0.5544	0.3717
	6	FMF-4-P	0.1201	0.5074	0.3873
	7	FOF-2	0.0402	0.4735	0.4333
	8	FMF-1-T	-0.0575	0.4211	0.4786
	9	FMOC-4	-0.1593	0.4005	0.5598
	10	FMF-5-S	-0.3204	0.3398	0.6602
	11	FMOC-3	-0.6271	0.1666	0.7937
	12	FMF-2-T	-0.6972	0.117	0.8141
Farmer F	Rank	action	Phi	Phi+	Phi-
	1	FMF-4-P	0.4347	0.6995	0.2648
	2	FMF-5-S	0.2949	0.6475	0.3525
	3	FOF-1	0.2045	0.5936	0.3892
	4	FMF-3-P	0.1982	0.5827	0.3845

	5	FMOC-4	0.1159	0.5529	0.437
	6	FMOC-2	0.0778	0.5318	0.454
	7	FMF-1-T	0.0514	0.5094	0.458
	8	FMOC-1	-0.0602	0.4699	0.5301
	9	FMOC-3	-0.2178	0.3896	0.6075
	10	FMOF	-0.2344	0.3639	0.5983
	11	FOF-2	-0.3183	0.3254	0.6436
	12	FMF-2-T	-0.5467	0.2154	0.7621
Farmer G	Rank	action	Phi	Phi+	Phi-
	1	FOF-1	0.5865	0.7571	0.1706
	2	FMOC-2	0.5672	0.7482	0.181
	3	FMOC-1	0.3905	0.6953	0.3047
	4	FOF-2	0.2543	0.5841	0.3298
	5	FMOC-4	0.049	0.5117	0.4627
	6	FMF-5-S	-0.0616	0.4692	0.5308
	7	FMF-4-P	-0.0675	0.3971	0.4646
	8	FMOF	-0.1455	0.354	0.4995
	9	FMF-3-P	-0.1597	0.3448	0.5045
	10	FMF-1-T	-0.2763	0.2935	0.5697
	11	FMOC-3	-0.3731	0.3105	0.6835
	12	FMF-2-T	-0.7636	0.0534	0.817
Farmer H	Rank	action	Phi	Phi+	Phi-
	1	FMF-4-P	0.3224	0.6397	0.3174
	2	FMF-3-P	0.2676	0.6076	0.34
	3	FMOC-4	0.2217	0.5981	0.3764
	4	FMOC-1	0.1705	0.5853	0.4147
	5	FMOC-2	0.1514	0.5663	0.4149
	6	FOF-1	0.1482	0.5611	0.4129
	7	FMOF	0.0734	0.5155	0.4421
	8	FMF-5-S	0.0138	0.5069	0.4931
	9	FMF-1-T	-0.1923	0.386	0.5783

	10	FMOC-3	-0.3211	0.3365	0.6575
	11	FOF-2	-0.3287	0.3157	0.6445
	12	FMF-2-T	-0.5269	0.2237	0.7506

Table D84. MCDA Results Based on Hypothetical (Multiple Perspective) Weighting Scenarios.

	Rank	action	Phi	Phi+	Phi-
EIM	1	FOF-1	0.5204	0.7408	0.2204
	2	FMF-5-S	0.3914	0.6957	0.3043
	3	FMOC-2	0.331	0.6493	0.3183
	4	FMF-4-P	0.2862	0.6172	0.331
	5	FMF-1-T	0.2156	0.5851	0.3696
	6	FOF-2	0.0197	0.4872	0.4675
	7	FMF-3-P	-0.0785	0.4349	0.5134
	8	FMOC-1	-0.0926	0.4537	0.5463
	9	FMOC-4	-0.1891	0.3957	0.5848
	10	FMOC-3	-0.2851	0.351	0.6361
	11	FMOF	-0.2873	0.3304	0.6178
	12	FMF-2-T	-0.8317	0.0647	0.8964
FPM	Rank	action	Phi	Phi+	Phi-
	1	FOF-1	0.5986	0.7799	0.1813
	2	FMOC-2	0.5657	0.7667	0.201
	3	FMOC-1	0.3769	0.6884	0.3116
	4	FMOF	0.3386	0.6434	0.3048
	5	FOF-2	0.0979	0.5263	0.4284
	6	FMF-3-P	0.0388	0.474	0.4351
	7	FMOC-4	0.0065	0.474	0.4675
	8	FMF-4-P	-0.0267	0.4607	0.4875
	9	FMF-5-S	-0.2344	0.3828	0.6172
	10	FMF-1-T	-0.4103	0.2722	0.6825
	11	FMOC-3	-0.5198	0.2336	0.7534

	12	FMF-2-T	-0.8317	0.0647	0.8964
CM	Rank	action	Phi	Phi+	Phi-
	1	FMF-4-P	0.4427	0.6954	0.2528
	2	FMF-5-S	0.3914	0.6957	0.3043
	3	FMF-3-P	0.3127	0.6304	0.3178
	4	FMOC-4	0.2021	0.5913	0.3893
	5	FOF-1	0.051	0.5061	0.4551
	6	FMOC-2	-0.0602	0.4537	0.5139
	7	FMF-1-T	-0.0974	0.4286	0.526
	8	FMOC-3	-0.1287	0.4292	0.5579
	9	FMOF	-0.1308	0.4087	0.5395
	10	FMOC-1	-0.1708	0.4146	0.5854
	11	FMF-2-T	-0.3623	0.2994	0.6617
	12	FOF-2	-0.4497	0.2525	0.7022
FMR	Rank	action	Phi	Phi+	Phi-
	1	FMOC-2	N/A*	N/A*	N/A*
	2	FMOC-1	N/A*	N/A*	N/A*
	3	FMF-4-P	0.2727	0.6104	0.3377
	4	FOF-1	N/A*	N/A*	N/A*
	4	FMOF	0.2208	0.5844	0.3636
	6	FMF-3-P	0.1688	0.5584	0.3896
	7	FMOC-4	N/A*	N/A*	N/A*
	8	FMF-1-T	-0.026	0.4675	0.4935
	9	FMF-5-S	-0.1169	0.4416	0.5584
	10	FOF-2	N/A*	N/A*	N/A*
	11	FMOC-3	N/A*	N/A*	N/A*
	12	FMF-2-T	-0.7143	0.1299	0.8442

*N/A: Not Applicable

Table D85. Summary of Farmers'used aquafeed and produced fish.

Farmer	Farm name	Aquafeed brand	Fish Produced

A	Lone Duck	Rangen	Tilapia
B	Rushing Waters Fisheries	Prairie Aquatech	Rainbow
C	Branch River Trout Hatchery	Bio Diet	Rainbow, Brook (trout), Atlantic salmon
D	Toal Lake Hatchery	Zeigler	Perch
E	Floating Lakes Aquaponics	Optimal Fish Food	Tilapia
F	Lyfe Gardens LLC	Purina	Tilapia
G	Lake Orchard Farm Aquaponics	Rangen	Tilapia (filleted)
H	Omega3 Greens LLC	TBD by Farmer	TBD by Farmer

Towards the Improvement of Science-Industry Communication in Aquafarming: Aiming the Big Picture

Advancements in science and technology have boosted aquaculture systems production yields in the last decades. However, the increase in productivity has been concurrent with elevated natural resources use and environmental impacts. Two vital steps need to be taken to sustain the growth of food production systems (including aquacultures) while conserving natural resources; (1) undertaking a systemic approach, and (2) filling the science-practice gap.

(1) Undertaking systems-oriented approach:

Many of the existing challenges that are directly and indirectly related to the food systems, are systematic challenges (e.g. ecosystems overuse, climate change, biodiversity, etc.). In addition, social and economic dimensions could pose additional considerations when dealing with such challenges. Hence, scientists and researchers should embrace the complexity and inter-connectedness nature of such systems to effectively tackle the malfunctions. For example, aquafeed is a critical part of aquafarming, as it provides the required energy input to achieve optimal and rapid growth for the rearing species. So, the improvement of aquafeed in a way that it elevates the production quantity should be integrated with the elevation in production quality, environmental performance, and economic favorability.

(2) Filling the science-practice gap:

The current science and technology in aquaculture shows a promising potential to tackle the complex challenges in this area. Nevertheless, to achieve sustainable aquaculture food production, strategies to facilitate the transmission of science among researchers, policy makers, and aquafarmers need to be implemented. Stakeholders with diverse backgrounds, skills, and priorities should be able to work together across different disciplines and multiple scales (Abate et al., 2009). Conducting research in the areas that directly aims the existing challenges of sustainable aquafarming (e.g. aquafeeds selection) and direct engagement of aquafarmers and stakeholders, who have plenty of practical knowledge, with researchers, who can propose innovative solutions to increase the sustainability of food production, can effectively contribute to reducing the gap between science and practice in this area.

Appendix E

Supplementary Information (SI) for chapter 7.

Table E86. County-Level Heating Demand Estimation.

County Code (GEOID)	County Name	FIPS Code	HDD 74* (in Fahrenheit)	HDD 74 (in Celsius)	BTUs (per m3)	KJ (per m3)	KJ (per kg.a) - Sc1 (0.54 m3/kg.a)	KJ (per kg.a) - Sc2 (0.05 m3/kg.a)	KJ (per kg.a) - Sc3 (0.01 m3/kg.a)
1	Adams	55001	10958	6087.78	5249.16	5537.86	2990.45	276.89	55.38
2	Ashland	55003	12253	6807.22	5868.07	6190.81	3343.04	309.54	61.91
3	Barron	55005	11694	6496.67	5600.80	5908.84	3190.78	295.44	59.09
4	Bayfield	55007	12253	6807.22	5868.07	6190.81	3343.04	309.54	61.91
5	Brown	55009	10535	5852.78	5046.87	5324.45	2875.20	266.22	53.24
6	Buffalo	55011	11221	6233.89	5374.84	5670.46	3062.05	283.52	56.70
7	Burnett	55013	11827	6570.56	5664.49	5976.04	3227.06	298.80	59.76
8	Calumet	55015	10498	5832.22	5028.79	5305.37	2864.90	265.27	53.05
9	Chippewa	55017	11221	6233.89	5374.84	5670.46	3062.05	283.52	56.70
10	Clark	55019	11405	6336.11	5462.64	5763.09	3112.07	288.15	57.63
11	Columbia	55021	10908	6060.00	5225.06	5512.44	2976.72	275.62	55.12
12	Crawford	55023	9910	5505.56	4747.74	5008.87	2704.79	250.44	50.09
13	Dane	55025	10128	5626.67	4851.90	5118.75	2764.13	255.94	51.19
14	Dodge	55027	10413	5785.00	4988.34	5262.70	2841.86	263.13	52.63

15	Door	55029	10535	5852.78	5046.87	5324.45	2875.20	266.22	53.24
16	Douglas	55031	12325	6847.22	5902.51	6227.15	3362.66	311.36	62.27
17	Dunn	55033	11221	6233.89	5374.84	5670.46	3062.05	283.52	56.70
18	Eau Claire	55035	11221	6233.89	5374.84	5670.46	3062.05	283.52	56.70
19	Florence	55037	11849	6582.78	5675.25	5987.39	3233.19	299.37	59.87
20	Fond du Lac	55039	10305	5725.00	4936.69	5208.21	2812.43	260.41	52.08
21	Forest	55041	12573	6985.00	6021.30	6352.47	3430.33	317.62	63.52
22	Grant	55043	9910	5505.56	4747.74	5008.87	2704.79	250.44	50.09
23	Green	55045	9904	5502.22	4744.73	5005.69	2703.07	250.28	50.06
24	Green Lake	55047	10498	5832.22	5028.79	5305.37	2864.90	265.27	53.05
25	Iowa	55049	9910	5505.56	4747.74	5008.87	2704.79	250.44	50.09
26	Iron	55051	12253	6807.22	5868.07	6190.81	3343.04	309.54	61.91
27	Jackson	55053	11357	6309.44	5439.83	5739.02	3099.07	286.95	57.39
28	Jefferson	55055	10732	5962.22	5140.70	5423.44	2928.66	271.17	54.23
29	Juneau	55057	11357	6309.44	5439.83	5739.02	3099.07	286.95	57.39
30	Kenosha	55059	9581	5322.78	4590.65	4843.14	2615.29	242.16	48.43
31	Kewaunee	55061	10535	5852.78	5046.87	5324.45	2875.20	266.22	53.24
32	La Crosse	55063	9896	5497.78	4741.29	5002.06	2701.11	250.10	50.02
33	Lafayette	55065	9904	5502.22	4744.73	5005.69	2703.07	250.28	50.06

34	Langlade	55067	11857	6587.22	5678.70	5991.03	3235.16	299.55	59.91
35	Lincoln	55069	11857	6587.22	5678.70	5991.03	3235.16	299.55	59.91
36	Manitowoc	55071	10673	5929.44	5112.72	5393.92	2912.72	269.70	53.94
37	Marathon	55073	11481	6378.33	5499.22	5801.68	3132.91	290.08	58.02
38	Marinette	55075	11849	6582.78	5675.25	5987.39	3233.19	299.37	59.87
39	Marquette	55077	10958	6087.78	5249.16	5537.86	2990.45	276.89	55.38
40	Milwaukee	55079	9523	5290.56	4562.67	4813.62	2599.35	240.68	48.14
41	Monroe	55081	9904	5502.22	4744.73	5005.69	2703.07	250.28	50.06
42	Oconto	55083	10535	5852.78	5046.87	5324.45	2875.20	266.22	53.24
43	Oneida	55085	11857	6587.22	5678.70	5991.03	3235.16	299.55	59.91
44	Outagamie	55087	10809	6005.00	5177.71	5462.48	2949.74	273.12	54.62
45	Ozaukee	55089	10673	5929.44	5112.72	5393.92	2912.72	269.70	53.94
46	Pepin	55091	10781	5989.44	5164.37	5448.41	2942.14	272.42	54.48
47	Pierce	55093	10781	5989.44	5164.37	5448.41	2942.14	272.42	54.48
48	Polk	55095	11394	6330.00	5457.47	5757.63	3109.12	287.88	57.58
49	Portage	55097	11881	6600.56	5690.32	6003.29	3241.78	300.16	60.03
50	Price	55099	12451	6917.22	5962.76	6290.71	3396.98	314.54	62.91
51	Racine	55101	9768	5426.67	4679.74	4937.13	2666.05	246.86	49.37
52	Richland	55103	9910	5505.56	4747.74	5008.87	2704.79	250.44	50.09

53	Rock	55105	9525	5291.67	4563.53	4814.52	2599.84	240.73	48.15
54	Rusk	55107	11694	6496.67	5600.80	5908.84	3190.78	295.44	59.09
55	Saint Croix	55109	11533	6407.22	5523.75	5827.56	3146.88	291.38	58.28
56	Sauk	55111	9910	5505.56	4747.74	5008.87	2704.79	250.44	50.09
57	Sawyer	55113	12115	6730.56	5802.22	6121.34	3305.52	306.07	61.21
58	Shawano	55115	10535	5852.78	5046.87	5324.45	2875.20	266.22	53.24
59	Sheboygan	55117	10673	5929.44	5112.72	5393.92	2912.72	269.70	53.94
60	Taylor	55119	12380	6877.78	5929.19	6255.30	3377.86	312.76	62.55
61	Trempealeau	55121	9896	5497.78	4741.29	5002.06	2701.11	250.10	50.02
62	Vernon	55123	11357	6309.44	5439.83	5739.02	3099.07	286.95	57.39
63	Vilas	55125	11865	6591.67	5682.57	5995.11	3237.36	299.76	59.95
64	Walworth	55127	9525	5291.67	4563.53	4814.52	2599.84	240.73	48.15
65	Washburn	55129	12115	6730.56	5802.22	6121.34	3305.52	306.07	61.21
66	Washington	55131	10662	5923.33	5107.56	5388.48	2909.78	269.42	53.88
67	Waukesha	55133	10732	5962.22	5140.70	5423.44	2928.66	271.17	54.23
68	Waupaca	55135	10254	5696.67	4912.16	5182.33	2798.46	259.12	51.82
69	Waushara	55137	10254	5696.67	4912.16	5182.33	2798.46	259.12	51.82
70	Winnebago	55139	10498	5832.22	5028.79	5305.37	2864.90	265.27	53.05
71	Wood	55141	10958	6087.78	5249.16	5537.86	2990.45	276.89	55.38

72	Menominee	55078	12392	6884.44	5934.79	6261.20	3381.05	313.06	62.61

* 2-year-average breakdown (2018 to 2019) heating degree days with a base temperature of 74 °F (23 °C) ("Degree Days Calculated Accurately for Locations Worldwide," 2020); Closest accurate weather station data is selected for each county.

Table E87. Required Space Estimation.

Scenario	Study	Effective Space (m3)	Live-weight fish produced (kg.a)	Effective Space m3 / kg.a	Species
SC1	Ghamkhar, Hartleb, et al. (2020)	155.35	284.67	0.545719605	Hybrid Walleye
SC2	Helfrich and Libey (2003)	464.5	45359.23	0.010240474	Not Specified
SC3	Walker (2017)	3716.1216	72574.7792	0.051204036	Salmon and Trout

Table E88. Flight Transportation Estimation.

Country	Amount* (in 1000 pounds)	Contribution (%)	Freight Distance (mi, to Chicago port)	Average Distance (mi)
China (Mainland)	268512	73.5%	7,069.08	5,195.05
China (Taiwan)	23408	6.4%	7,534.55	482.71
Indonesia	13973	3.8%	9,377.61	358.63

Ecuador	4008	1.1%	3,036.37	33.31
Honduras	17450	4.8%	1,857.01	88.69
Costa Rica	9569	2.6%	2,231.28	58.44
Columbia	10108	2.8%	2,763.18	76.44
Thailand	3032	0.8%	8,438.67	70.03
Mexico	6391	1.7%	1,543.72	27.00
Vietnam	2755	0.8%	8,310.77	62.67
Panama	358	0.1%	2,317.80	2.27
Brazil	1798	0.5%	4,138.65	20.37
Malaysia	941	0.3%	9,125.33	23.50
Hong Kong	48	0.0%	7,787.21	1.02
Peru	403	0.1%	3,669.07	4.05
Philipines	475	0.1%	8,219.96	10.69
Myanmar	1268	0.3%	8,090.54	28.08
Nicaragua	7	0.0%	2,000.33	0.04
India	41	0.0%	7,945.78	0.89
Chile	122	0.0%	5,078.12	1.70
Pakistan	158	0.0%	7,274.41	3.15
Bangladesh	258	0.1%	7,886.99	5.57

Other (Proxy: Canada)	290	0.1%	1,672.75	1.33
Total	365373	100%	Average distance per unit fish	6,555.61 (10550.23 km)

* Based on 2016 US tilapia imports (Aquaponics).

Table E89. Land Transportation Estimation (Georg).

County	County Code (GEOID)	FIPS	County to Chicago Driving route (mi)	County to Chicago Driving route (km)	County to Milwaukee Driving route (mi)	County to Milwaukee Driving route (km)	County to Minneapolis Driving route (mi)	County to Minneapolis Driving route (km)
Adams	1	55001	222.61	358.17949	147.25	236.9253	211.66	340.5609
Ashland	2	55003	400.5	644.4045	312.09	502.1528	193.58	311.4702
Barron	3	55005	371.73	598.11357	294.63	474.0597	92.05	148.1085
Bayfield	4	55007	463.77	746.20593	360.03	579.2883	216.35	348.1072
Brown	5	55009	202.18	325.30762	117.22	188.607	284.36	457.5352
Buffalo	6	55011	330.76	532.19284	253.57	407.9941	118.12	190.0551
Burnett	7	55013	419.44	674.87896	342.57	551.1951	80.24	129.1062
Calumet	8	55015	170.37	274.12533	89.5	144.0055	316.1	508.6049
Chippewa	9	55017	341.54	549.53786	266.16	428.2514	98.02	157.7142
Clark	10	55019	302.48	486.69032	213.95	344.2456	153.83	247.5125

Columbia	11	55021	172.97	278.30873	96.29	154.9306	246.43	396.5059
Crawford	12	55023	233.21	375.23489	166.18	267.3836	211.12	339.6921
Dane	13	55025	151.33	243.48997	78.4	126.1456	269.87	434.2208
Dodge	14	55027	146.37	235.50933	57.71	92.85539	285.66	459.6269
Door	15	55029	232.62	374.28558	150.23	241.7201	313.5	504.4215
Douglas	16	55031	445.94	717.51746	369.13	593.9302	154.49	248.5744
Dunn	17	55033	346.37	557.30933	269.32	433.3359	79.63	128.1247
Eau Claire	18	55035	311.52	501.23568	234.51	377.3266	92.14	148.2533
Florence	19	55037	321.6	517.4544	236.69	380.8342	298.02	479.5142
Fond du Lac	20	55039	149.64	240.77076	60.6	97.5054	304.09	489.2808
Forest	21	55041	314.73	506.40057	229.65	369.5069	276.89	445.516
Grant	22	55043	205.77	331.08393	157.78	253.868	248.19	399.3377
Green	23	55045	136.67	219.90203	108.11	173.949	293.06	471.5335
Green Lake	24	55047	184.27	296.49043	95.54	153.7239	252.84	406.8196
Iowa	25	55049	179.46	288.75114	121.64	195.7188	264.77	426.0149
Iron	26	55051	380	611.42	291.73	469.3936	232.72	374.4465
Jackson	27	55053	270.44	435.13796	193.49	311.3254	143.75	231.2938
Jefferson	28	55055	121.99	196.28191	47.13	75.83217	297.15	478.1144
Juneau	29	55057	227.1	365.4039	150.04	241.4144	194.29	312.6126

Kenosha	30	55059	63.06	101.46354	40.77	65.59893	374.14	601.9913
Kewaunee	31	55061	207.26	333.48134	122.51	197.1186	309.13	497.3902
La Crosse	32	55063	273.32	439.77188	195.83	315.0905	155.9	250.8431
Lafayette	33	55065	165.29	265.95161	135.64	218.2448	289.3	465.4837
Langlade	34	55067	278.83	448.63747	190.38	306.3214	231.36	372.2582
Lincoln	35	55069	299.61	482.07249	211.31	339.9978	212.32	341.6229
Manitowoc	36	55071	173.41	279.01669	88.45	142.3161	318.76	512.8848
Marathon	37	55073	267.66	430.66494	179.18	288.3006	181.76	292.4518
Marinette	38	55075	271.63	437.05267	186.73	300.4486	289.61	465.9825
Marquette	39	55077	202.93	326.51437	126.13	202.9432	231.92	373.1593
Milwaukee	40	55079	89.17	143.47453	0	0	333.96	537.3416
Monroe	41	55081	250.31	402.74879	172.93	278.2444	180.64	290.6498
Oconto	42	55083	251.4	404.5026	172.93	278.2444	272.72	438.8065
Oneida	43	55085	332.06	534.28454	244.06	392.6925	245.07	394.3176
Outagamie	44	55087	202.54	325.88686	113.92	183.2973	272.59	438.5973
Ozaukee	45	55089	113.78	183.07202	28.62	46.04958	323.54	520.5759
Pepin	46	55091	338.83	545.17747	261.57	420.8661	76.28	122.7345
Pierce	47	55093	364.32	586.19088	287.05	461.8635	55.48	89.26732
Polk	48	55095	399.98	643.56782	322.87	519.4978	65.68	105.6791

Portage	49	55097	244.86	393.97974	145.51	234.1256	222.35	357.7612
Price	50	55099	357.67	575.49103	269.26	433.2393	174.85	281.3337
Racine	51	55101	70.27	113.06443	27.1	43.6039	360.4	579.8836
Richland	52	55103	216.23	347.91407	142.23	228.8481	217.77	350.3919
Rock	53	55105	111.31	179.09779	80.16	128.9774	311.52	501.2357
Rusk	54	55107	363.97	585.62773	287.03	461.8313	128.2	206.2738
Saint Croix	55	55109	375.97	604.93573	298.85	480.8497	45.93	73.90137
Sauk	56	55111	204.83	329.57147	127.12	204.5361	237.8	382.6202
Sawyer	57	55113	405.5	652.4495	329.04	529.4254	149.72	240.8995
Shawano	58	55115	247.8	398.7102	152.15	244.8094	236.75	380.9308
Sheboygan	59	55117	136.53	219.67677	52.25	84.07025	332.43	534.8799
Taylor	60	55119	328.18	528.04162	239.87	385.9508	164.12	264.0691
Trempealeau	61	55121	305.24	491.13116	227.86	366.6267	144.94	233.2085
Vernon	62	55123	245.35	394.76815	171.32	275.6539	190.18	305.9996
Vilas	63	55125	359.91	579.09519	271.64	437.0688	272.66	438.7099
Walworth	64	55127	85.48	137.53732	40.13	64.56917	325.31	523.4238
Washburn	65	55129	403.93	649.92337	327.17	526.4165	118.25	190.2643
Washington	66	55131	120.51	193.90059	31.83	51.21447	313.18	503.9066
Waukesha	67	55133	107.95	173.69155	19.38	31.18242	316.57	509.3611

Waupaca	68	55135	218.47	351.51823	129.92	209.0413	246.95	397.3426
Waushara	69	55137	208.21	335.00989	119.55	192.356	239.27	384.9854
Winnebago	70	55139	181.15	291.47035	92.5	148.8325	268.51	432.0326
Wood	71	55141	261.53	420.80177	178.07	286.5146	179.61	288.9925
Menominee	72	55078	264.08	424.90472	168.65	271.3579	239.94	386.0635

Table E90. Unit Environmental Impacts of heat (per kJ).*

Impact category	Unit	Total	Natural gas, combusted in industrial equipment/RNA	Natural gas, processed, at plant/US	Transport, combination truck, average fuel mix/US	Transport, train, diesel powered/US
Ozone depletion	kg CFC-11 eq	4.58E-17	0	2.69E-17	1.87E-17	2.65E-19
Global warming	kg CO2 eq	6.4E-05	5.22E-05	1.13E-05	4.89E-07	6.94E-09
Smog	kg O3 eq	1.4E-06	1.1E-06	2.11E-07	8E-08	4.03E-09
Acidification	kg SO2 eq	5.47E-07	3.13E-08	5.13E-07	2.92E-09	1.24E-10
Eutrophication	kg N eq	5.39E-09	1.96E-09	3.26E-09	1.63E-10	7.5E-12
Carcinogenics	CTUh	2.7E-13	4.15E-15	2.59E-13	6.7E-15	9.53E-17
Non carcinogenics	CTUh	3.37E-12	2.16E-15	3.3E-12	6.45E-14	9.18E-16
Respiratory effects	kg PM2.5 eq	3.22E-08	9.74E-10	3.11E-08	5.09E-11	2.3E-12
Ecotoxicity	CTUe	8.56E-05	8.61E-09	8.43E-05	1.25E-06	1.78E-08

Fossil fuel depletion	MJ surplus	0.000167	0	0.000166	9.37E-07	1.33E-08

* Product: (1 kJ) 26.5738354 cm3 Natural gas(Deru & Torcellini, 2007), combusted in industrial equipment/RNA (of project USLCI); Method: TRACI 2.1 V1.04 / US 2008.

Table E91. Unit Environmental Impacts of Land Transportation (per t.km).*

Impact category	Unit	Total	Operation, reefer, freezing {GLO}| market for | Cut-off, U	Transport, freight, lorry >32 metric ton, EURO3 {GLO}| market for | Cut-off, U	Transport, freight, lorry >32 metric ton, EURO4 {GLO}| market for | Cut-off, U	Transport, freight, lorry >32 metric ton, EURO5 {GLO}| market for | Cut-off, U	Transport, freight, lorry >32 metric ton, EURO6 {GLO}| market for | Cut-off, U	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Cut-off, U	Transport, freight, lorry 16-32 metric ton, EURO4 {GLO}| market for | Cut-off, U	Transport, freight, lorry 16-32 metric ton, EURO5 {GLO}| market for | Cut-off, U	Transport, freight, lorry 16-32 metric ton, EURO6 {GLO}| market for | Cut-off, U
Ozone depletion	kg CFC-11 eq	3.01E-08	1.15E-09	6.52E-09	5.93E-09	2.16E-09	3.6E-10	6.55E-09	5.34E-09	1.78E-09	3.12E-10
Global warming	kg CO2 eq	0.121142	0.004829	0.025616	0.023319	0.008554	0.001365	0.026847	0.021941	0.007381	0.001291
Smog	kg O3 eq	0.016822	0.001705	0.004403	0.002525	0.000668	5.74E-05	0.004489	0.002375	0.000554	4.39E-05
Acidification	kg SO2 eq	0.000658	5.78E-05	0.000163	0.000106	3.16E-05	3.74E-06	0.000167	9.99E-05	2.66E-05	3.17E-06
Eutrophication	kg N eq	0.000139	7.67E-06	3.06E-05	2.54E-05	8.78E-06	1.37E-06	3.24E-05	2.42E-05	7.65E-06	1.26E-06
Carcinogenics	CTUh	3.6E-09	2.19E-10	6.96E-10	6.36E-10	2.32E-10	3.86E-11	8.32E-10	6.78E-10	2.26E-10	4.02E-11

Non carcinogenics	CTUh	2.82E-08	8.05E-10	6.17E-09	5.64E-09	2.05E-09	3.42E-10	6.18E-09	5.02E-09	1.67E-09	2.98E-10
Respiratory effects	kg PM2.5 eq	9.23E-05	1E-05	2.13E-05	1.69E-05	6.08E-06	9.72E-07	1.91E-05	1.29E-05	4.23E-06	7.11E-07
Ecotoxicity	CTUe	0.691719	0.027405	0.148275	0.136898	0.049799	0.008292	0.149617	0.123061	0.041063	0.007309
Fossil fuel depletion	MJ surplus	0.268839	0.009419	0.058303	0.05298	0.019286	0.003214	0.058825	0.047992	0.016018	0.002804

* Product: 1 tkm Transport, freight, lorry with reefer, freezing (Ziegler et al.)| processing | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit); Method: TRACI 2.1 V1.04 / US 2008.

Table E92.Total Environmental Impacts of Flight Transportation (per ton of commodity).

Impact category	Unit	Total	Operation, reefer, freezing {GLO}| market for | Cut-off, U	Transport, freight, aircraft {GLO}| market for | Cut-off, U
Ozone depletion	kg CFC-11 eq	0.002869	1.09E-06	0.002868
Global warming	kg CO2 eq	11751.69	4.584834	11747.1
Smog	kg O3 eq	1239.121	1.619341	1237.501
Acidification	kg SO2 eq	51.04629	0.054844	50.99144
Eutrophication	kg N eq	7.987896	0.007285	7.980611
Carcinogenics	CTUh	6.95E-05	2.08E-07	6.93E-05
Non carcinogenics	CTUh	0.0003	7.64E-07	0.000299
Respiratory effects	kg PM2.5 eq	2.445686	0.009518	2.436168

Ecotoxicity	CTUe	6227.575	26.02133	6201.553
Fossil fuel depletion	MJ surplus	25427.25	8.943303	25418.31

* Product: 10550.23 tkm Transport, freight, aircraft with reefer, freezing {GLO}| processing | Cut-off, U (of project Ecoinvent 3 - allocation, cut-off by classification - unit); Method: TRACI 2.1 V1.04 / US 2008.

Table E93. County-Level Land Transportation Environmental Impacts (Consumption in Chicago).

County	Driving route	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
Unit	km	kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	CTUh	CTUh	kg PM2.5 eq	CTUe	MJ surplus
Adams	3.58E+02	1.08E-05	4.34E+01	6.03E+00	2.36E-01	4.99E-02	1.29E-06	1.01E-05	3.30E-02	2.48E+02	9.63E+01
Ashland	6.44E+02	1.94E-05	7.81E+01	1.08E+01	4.24E-01	8.98E-02	2.32E-06	1.82E-05	5.95E-02	4.46E+02	1.73E+02
Barron	5.98E+02	1.80E-05	7.25E+01	1.01E+01	3.94E-01	8.33E-02	2.15E-06	1.69E-05	5.52E-02	4.14E+02	1.61E+02
Bayfield	7.46E+02	2.25E-05	9.04E+01	1.26E+01	4.91E-01	1.04E-01	2.68E-06	2.10E-05	6.88E-02	5.16E+02	2.01E+02
Brown	3.25E+02	9.79E-06	3.94E+01	5.47E+00	2.14E-01	4.53E-02	1.17E-06	9.17E-06	3.00E-02	2.25E+02	8.75E+01
Buffalo	5.32E+02	1.60E-05	6.45E+01	8.95E+00	3.50E-01	7.41E-02	1.91E-06	1.50E-05	4.91E-02	3.68E+02	1.43E+02
Burnett	6.75E+02	2.03E-05	8.18E+01	1.14E+01	4.44E-01	9.40E-02	2.43E-06	1.90E-05	6.23E-02	4.67E+02	1.81E+02
Calumet	2.74E+02	8.25E-06	3.32E+01	4.61E+00	1.80E-01	3.82E-02	9.86E-07	7.73E-06	2.53E-02	1.90E+02	7.37E+01
Chippewa	5.50E+02	1.65E-05	6.66E+01	9.24E+00	3.62E-01	7.66E-02	1.98E-06	1.55E-05	5.07E-02	3.80E+02	1.48E+02

Clark	4.87E+02	1.47E-05	5.90E+01	8.19E+00	3.20E-01	6.78E-02	1.75E-06	1.37E-05	4.49E-02	3.37E+02	1.31E+02
Columbia	2.78E+02	8.38E-06	3.37E+01	4.68E+00	1.83E-01	3.88E-02	1.00E-06	7.84E-06	2.57E-02	1.93E+02	7.48E+01
Crawford	3.75E+02	1.13E-05	4.55E+01	6.31E+00	2.47E-01	5.23E-02	1.35E-06	1.06E-05	3.46E-02	2.60E+02	1.01E+02
Dane	2.43E+02	7.33E-06	2.95E+01	4.10E+00	1.60E-01	3.39E-02	8.76E-07	6.86E-06	2.25E-02	1.68E+02	6.55E+01
Dodge	2.36E+02	7.09E-06	2.85E+01	3.96E+00	1.55E-01	3.28E-02	8.47E-07	6.64E-06	2.17E-02	1.63E+02	6.33E+01
Door	3.74E+02	1.13E-05	4.53E+01	6.30E+00	2.46E-01	5.21E-02	1.35E-06	1.05E-05	3.45E-02	2.59E+02	1.01E+02
Douglas	7.18E+02	2.16E-05	8.69E+01	1.21E+01	4.72E-01	1.00E-01	2.58E-06	2.02E-05	6.62E-02	4.96E+02	1.93E+02
Dunn	5.57E+02	1.68E-05	6.75E+01	9.37E+00	3.67E-01	7.76E-02	2.01E-06	1.57E-05	5.14E-02	3.86E+02	1.50E+02
Eau Claire	5.01E+02	1.51E-05	6.07E+01	8.43E+00	3.30E-01	6.98E-02	1.80E-06	1.41E-05	4.62E-02	3.47E+02	1.35E+02
Florence	5.17E+02	1.56E-05	6.27E+01	8.70E+00	3.41E-01	7.21E-02	1.86E-06	1.46E-05	4.77E-02	3.58E+02	1.39E+02
Fond du Lac	2.41E+02	7.25E-06	2.92E+01	4.05E+00	1.58E-01	3.35E-02	8.66E-07	6.79E-06	2.22E-02	1.67E+02	6.47E+01
Forest	5.06E+02	1.52E-05	6.13E+01	8.52E+00	3.33E-01	7.06E-02	1.82E-06	1.43E-05	4.67E-02	3.50E+02	1.36E+02
Grant	3.31E+02	9.97E-06	4.01E+01	5.57E+00	2.18E-01	4.61E-02	1.19E-06	9.33E-06	3.05E-02	2.29E+02	8.90E+01
Green	2.20E+02	6.62E-06	2.66E+01	3.70E+00	1.45E-01	3.06E-02	7.91E-07	6.20E-06	2.03E-02	1.52E+02	5.91E+01
Green Lake	2.96E+02	8.93E-06	3.59E+01	4.99E+00	1.95E-01	4.13E-02	1.07E-06	8.36E-06	2.74E-02	2.05E+02	7.97E+01
Iowa	2.89E+02	8.69E-06	3.50E+01	4.86E+00	1.90E-01	4.02E-02	1.04E-06	8.14E-06	2.66E-02	2.00E+02	7.76E+01
Iron	6.11E+02	1.84E-05	7.41E+01	1.03E+01	4.02E-01	8.52E-02	2.20E-06	1.72E-05	5.64E-02	4.23E+02	1.64E+02
Jackson	4.35E+02	1.31E-05	5.27E+01	7.32E+00	2.86E-01	6.06E-02	1.57E-06	1.23E-05	4.01E-02	3.01E+02	1.17E+02
Jefferson	1.96E+02	5.91E-06	2.38E+01	3.30E+00	1.29E-01	2.73E-02	7.06E-07	5.53E-06	1.81E-02	1.36E+02	5.28E+01

Juneau	3.65E+02	1.10E-05	4.43E+01	6.15E+00	2.41E-01	5.09E-02	1.31E-06	1.03E-05	3.37E-02	2.53E+02	9.82E+01
Kenosha	1.01E+02	3.05E-06	1.23E+01	1.71E+00	6.68E-02	1.41E-02	3.65E-07	2.86E-06	9.36E-03	7.02E+01	2.73E+01
Kewaunee	3.33E+02	1.00E-05	4.04E+01	5.61E+00	2.20E-01	4.65E-02	1.20E-06	9.40E-06	3.08E-02	2.31E+02	8.97E+01
La Crosse	4.40E+02	1.32E-05	5.33E+01	7.40E+00	2.89E-01	6.13E-02	1.58E-06	1.24E-05	4.06E-02	3.04E+02	1.18E+02
Lafayette	2.66E+02	8.01E-06	3.22E+01	4.47E+00	1.75E-01	3.71E-02	9.57E-07	7.50E-06	2.45E-02	1.84E+02	7.15E+01
Langlade	4.49E+02	1.35E-05	5.43E+01	7.55E+00	2.95E-01	6.25E-02	1.61E-06	1.26E-05	4.14E-02	3.10E+02	1.21E+02
Lincoln	4.82E+02	1.45E-05	5.84E+01	8.11E+00	3.17E-01	6.72E-02	1.73E-06	1.36E-05	4.45E-02	3.33E+02	1.30E+02
Manitowoc	2.79E+02	8.40E-06	3.38E+01	4.69E+00	1.84E-01	3.89E-02	1.00E-06	7.86E-06	2.57E-02	1.93E+02	7.50E+01
Marathon	4.31E+02	1.30E-05	5.22E+01	7.24E+00	2.83E-01	6.00E-02	1.55E-06	1.21E-05	3.97E-02	2.98E+02	1.16E+02
Marinette	4.37E+02	1.32E-05	5.29E+01	7.35E+00	2.88E-01	6.09E-02	1.57E-06	1.23E-05	4.03E-02	3.02E+02	1.17E+02
Marquette	3.27E+02	9.83E-06	3.96E+01	5.49E+00	2.15E-01	4.55E-02	1.17E-06	9.20E-06	3.01E-02	2.26E+02	8.78E+01
Milwaukee	1.43E+02	4.32E-06	1.74E+01	2.41E+00	9.44E-02	2.00E-02	5.16E-07	4.04E-06	1.32E-02	9.92E+01	3.86E+01
Monroe	4.03E+02	1.21E-05	4.88E+01	6.77E+00	2.65E-01	5.61E-02	1.45E-06	1.14E-05	3.72E-02	2.79E+02	1.08E+02
Oconto	4.05E+02	1.22E-05	4.90E+01	6.80E+00	2.66E-01	5.64E-02	1.46E-06	1.14E-05	3.73E-02	2.80E+02	1.09E+02
Oneida	5.34E+02	1.61E-05	6.47E+01	8.99E+00	3.52E-01	7.44E-02	1.92E-06	1.51E-05	4.93E-02	3.70E+02	1.44E+02
Outagamie	3.26E+02	9.81E-06	3.95E+01	5.48E+00	2.15E-01	4.54E-02	1.17E-06	9.19E-06	3.01E-02	2.25E+02	8.76E+01
Ozaukee	1.83E+02	5.51E-06	2.22E+01	3.08E+00	1.21E-01	2.55E-02	6.59E-07	5.16E-06	1.69E-02	1.27E+02	4.92E+01
Pepin	5.45E+02	1.64E-05	6.60E+01	9.17E+00	3.59E-01	7.60E-02	1.96E-06	1.54E-05	5.03E-02	3.77E+02	1.47E+02
Pierce	5.86E+02	1.76E-05	7.10E+01	9.86E+00	3.86E-01	8.17E-02	2.11E-06	1.65E-05	5.41E-02	4.05E+02	1.58E+02

Polk	6.44E+02	1.94E-05	7.80E+01	1.08E+01	4.24E-01	8.97E-02	2.32E-06	1.81E-05	5.94E-02	4.45E+02	1.73E+02
Portage	3.94E+02	1.19E-05	4.77E+01	6.63E+00	2.59E-01	5.49E-02	1.42E-06	1.11E-05	3.64E-02	2.73E+02	1.06E+02
Price	5.75E+02	1.73E-05	6.97E+01	9.68E+00	3.79E-01	8.02E-02	2.07E-06	1.62E-05	5.31E-02	3.98E+02	1.55E+02
Racine	1.13E+02	3.40E-06	1.37E+01	1.90E+00	7.44E-02	1.58E-02	4.07E-07	3.19E-06	1.04E-02	7.82E+01	3.04E+01
Richland	3.48E+02	1.05E-05	4.21E+01	5.85E+00	2.29E-01	4.85E-02	1.25E-06	9.81E-06	3.21E-02	2.41E+02	9.35E+01
Rock	1.79E+02	5.39E-06	2.17E+01	3.01E+00	1.18E-01	2.50E-02	6.44E-07	5.05E-06	1.65E-02	1.24E+02	4.81E+01
Rusk	5.86E+02	1.76E-05	7.09E+01	9.85E+00	3.85E-01	8.16E-02	2.11E-06	1.65E-05	5.40E-02	4.05E+02	1.57E+02
Saint Croix	6.05E+02	1.82E-05	7.33E+01	1.02E+01	3.98E-01	8.43E-02	2.18E-06	1.71E-05	5.58E-02	4.18E+02	1.63E+02
Sauk	3.30E+02	9.92E-06	3.99E+01	5.54E+00	2.17E-01	4.59E-02	1.19E-06	9.29E-06	3.04E-02	2.28E+02	8.86E+01
Sawyer	6.52E+02	1.96E-05	7.90E+01	1.10E+01	4.29E-01	9.09E-02	2.35E-06	1.84E-05	6.02E-02	4.51E+02	1.75E+02
Shawano	3.99E+02	1.20E-05	4.83E+01	6.71E+00	2.62E-01	5.56E-02	1.43E-06	1.12E-05	3.68E-02	2.76E+02	1.07E+02
Sheboygan	2.20E+02	6.61E-06	2.66E+01	3.70E+00	1.45E-01	3.06E-02	7.90E-07	6.19E-06	2.03E-02	1.52E+02	5.91E+01
Taylor	5.28E+02	1.59E-05	6.40E+01	8.88E+00	3.48E-01	7.36E-02	1.90E-06	1.49E-05	4.87E-02	3.65E+02	1.42E+02
Trempealeau	4.91E+02	1.48E-05	5.95E+01	8.26E+00	3.23E-01	6.84E-02	1.77E-06	1.38E-05	4.53E-02	3.40E+02	1.32E+02
Vernon	3.95E+02	1.19E-05	4.78E+01	6.64E+00	2.60E-01	5.50E-02	1.42E-06	1.11E-05	3.64E-02	2.73E+02	1.06E+02
Vilas	5.79E+02	1.74E-05	7.02E+01	9.74E+00	3.81E-01	8.07E-02	2.08E-06	1.63E-05	5.34E-02	4.01E+02	1.56E+02
Walworth	1.38E+02	4.14E-06	1.67E+01	2.31E+00	9.05E-02	1.92E-02	4.95E-07	3.88E-06	1.27E-02	9.51E+01	3.70E+01
Washburn	6.50E+02	1.96E-05	7.87E+01	1.09E+01	4.28E-01	9.06E-02	2.34E-06	1.83E-05	6.00E-02	4.50E+02	1.75E+02
Washington	1.94E+02	5.84E-06	2.35E+01	3.26E+00	1.28E-01	2.70E-02	6.98E-07	5.47E-06	1.79E-02	1.34E+02	5.21E+01

Waukesha	1.74E+02	5.23E-06	2.10E+01	2.92E+00	1.14E-01	2.42E-02	6.25E-07	4.90E-06	1.60E-02	1.20E+02	4.67E+01
Waupaca	3.52E+02	1.06E-05	4.26E+01	5.91E+00	2.31E-01	4.90E-02	1.26E-06	9.91E-06	3.24E-02	2.43E+02	9.45E+01
Waushara	3.35E+02	1.01E-05	4.06E+01	5.64E+00	2.21E-01	4.67E-02	1.21E-06	9.44E-06	3.09E-02	2.32E+02	9.01E+01
Winnebago	2.91E+02	8.78E-06	3.53E+01	4.90E+00	1.92E-01	4.06E-02	1.05E-06	8.22E-06	2.69E-02	2.02E+02	7.84E+01
Wood	4.21E+02	1.27E-05	5.10E+01	7.08E+00	2.77E-01	5.86E-02	1.51E-06	1.19E-05	3.88E-02	2.91E+02	1.13E+02
Menominee	4.25E+02	1.28E-05	5.15E+01	7.15E+00	2.80E-01	5.92E-02	1.53E-06	1.20E-05	3.92E-02	2.94E+02	1.14E+02

Table E94. County-Level Land Transportation Environmental Impacts (Consumption in Milwaukee).

County	Driving route	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
Unit	km	kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	CTUh	CTUh	kg PM2.5 eq	CTUe	MJ surplus
Adams	2.37E+02	7.13E-06	2.87E+01	3.99E+00	1.56E-01	3.30E-02	8.52E-07	6.68E-06	2.19E-02	1.64E+02	6.37E+01
Ashland	5.02E+02	1.51E-05	6.08E+01	8.45E+00	3.31E-01	7.00E-02	1.81E-06	1.42E-05	4.63E-02	3.47E+02	1.35E+02
Barron	4.74E+02	1.43E-05	5.74E+01	7.97E+00	3.12E-01	6.60E-02	1.71E-06	1.34E-05	4.37E-02	3.28E+02	1.27E+02
Bayfield	5.79E+02	1.74E-05	7.02E+01	9.74E+00	3.81E-01	8.07E-02	2.08E-06	1.63E-05	5.34E-02	4.01E+02	1.56E+02
Brown	1.89E+02	5.68E-06	2.28E+01	3.17E+00	1.24E-01	2.63E-02	6.79E-07	5.32E-06	1.74E-02	1.30E+02	5.07E+01
Buffalo	4.08E+02	1.23E-05	4.94E+01	6.86E+00	2.69E-01	5.68E-02	1.47E-06	1.15E-05	3.76E-02	2.82E+02	1.10E+02

Burnett	5.51E+02	1.66E-05	6.68E+01	9.27E+00	3.63E-01	7.68E-02	1.98E-06	1.55E-05	5.09E-02	3.81E+02	1.48E+02
Calumet	1.44E+02	4.34E-06	1.74E+01	2.42E+00	9.48E-02	2.01E-02	5.18E-07	4.06E-06	1.33E-02	9.96E+01	3.87E+01
Chippewa	4.28E+02	1.29E-05	5.19E+01	7.20E+00	2.82E-01	5.97E-02	1.54E-06	1.21E-05	3.95E-02	2.96E+02	1.15E+02
Clark	3.44E+02	1.04E-05	4.17E+01	5.79E+00	2.27E-01	4.80E-02	1.24E-06	9.70E-06	3.18E-02	2.38E+02	9.25E+01
Columbia	1.55E+02	4.66E-06	1.88E+01	2.61E+00	1.02E-01	2.16E-02	5.57E-07	4.37E-06	1.43E-02	1.07E+02	4.17E+01
Crawford	2.67E+02	8.05E-06	3.24E+01	4.50E+00	1.76E-01	3.73E-02	9.62E-07	7.54E-06	2.47E-02	1.85E+02	7.19E+01
Dane	1.26E+02	3.80E-06	1.53E+01	2.12E+00	8.30E-02	1.76E-02	4.54E-07	3.56E-06	1.16E-02	8.73E+01	3.39E+01
Dodge	9.29E+01	2.80E-06	1.12E+01	1.56E+00	6.11E-02	1.29E-02	3.34E-07	2.62E-06	8.57E-03	6.42E+01	2.50E+01
Door	2.42E+02	7.28E-06	2.93E+01	4.07E+00	1.59E-01	3.37E-02	8.70E-07	6.81E-06	2.23E-02	1.67E+02	6.50E+01
Douglas	5.94E+02	1.79E-05	7.20E+01	9.99E+00	3.91E-01	8.27E-02	2.14E-06	1.67E-05	5.48E-02	4.11E+02	1.60E+02
Dunn	4.33E+02	1.30E-05	5.25E+01	7.29E+00	2.85E-01	6.04E-02	1.56E-06	1.22E-05	4.00E-02	3.00E+02	1.16E+02
Eau Claire	3.77E+02	1.14E-05	4.57E+01	6.35E+00	2.48E-01	5.26E-02	1.36E-06	1.06E-05	3.48E-02	2.61E+02	1.01E+02
Florence	3.81E+02	1.15E-05	4.61E+01	6.41E+00	2.51E-01	5.31E-02	1.37E-06	1.07E-05	3.51E-02	2.63E+02	1.02E+02
Fond du Lac	9.75E+01	2.94E-06	1.18E+01	1.64E+00	6.42E-02	1.36E-02	3.51E-07	2.75E-06	9.00E-03	6.74E+01	2.62E+01
Forest	3.70E+02	1.11E-05	4.48E+01	6.22E+00	2.43E-01	5.15E-02	1.33E-06	1.04E-05	3.41E-02	2.56E+02	9.93E+01
Grant	2.54E+02	7.64E-06	3.08E+01	4.27E+00	1.67E-01	3.54E-02	9.13E-07	7.16E-06	2.34E-02	1.76E+02	6.82E+01
Green	1.74E+02	5.24E-06	2.11E+01	2.93E+00	1.15E-01	2.42E-02	6.26E-07	4.90E-06	1.60E-02	1.20E+02	4.68E+01
Green Lake	1.54E+02	4.63E-06	1.86E+01	2.59E+00	1.01E-01	2.14E-02	5.53E-07	4.33E-06	1.42E-02	1.06E+02	4.13E+01
Iowa	1.96E+02	5.89E-06	2.37E+01	3.29E+00	1.29E-01	2.73E-02	7.04E-07	5.52E-06	1.81E-02	1.35E+02	5.26E+01

Iron	4.69E+02	1.41E-05	5.69E+01	7.90E+00	3.09E-01	6.54E-02	1.69E-06	1.32E-05	4.33E-02	3.25E+02	1.26E+02
Jackson	3.11E+02	9.37E-06	3.77E+01	5.24E+00	2.05E-01	4.34E-02	1.12E-06	8.78E-06	2.87E-02	2.15E+02	8.37E+01
Jefferson	7.58E+01	2.28E-06	9.19E+00	1.28E+00	4.99E-02	1.06E-02	2.73E-07	2.14E-06	7.00E-03	5.25E+01	2.04E+01
Juneau	2.41E+02	7.27E-06	2.92E+01	4.06E+00	1.59E-01	3.36E-02	8.69E-07	6.80E-06	2.23E-02	1.67E+02	6.49E+01
Kenosha	6.56E+01	1.97E-06	7.95E+00	1.10E+00	4.32E-02	9.14E-03	2.36E-07	1.85E-06	6.05E-03	4.54E+01	1.76E+01
Kewaunee	1.97E+02	5.93E-06	2.39E+01	3.32E+00	1.30E-01	2.75E-02	7.09E-07	5.56E-06	1.82E-02	1.36E+02	5.30E+01
La Crosse	3.15E+02	9.49E-06	3.82E+01	5.30E+00	2.07E-01	4.39E-02	1.13E-06	8.88E-06	2.91E-02	2.18E+02	8.47E+01
Lafayette	2.18E+02	6.57E-06	2.64E+01	3.67E+00	1.44E-01	3.04E-02	7.85E-07	6.15E-06	2.01E-02	1.51E+02	5.87E+01
Langlade	3.06E+02	9.22E-06	3.71E+01	5.15E+00	2.02E-01	4.27E-02	1.10E-06	8.63E-06	2.83E-02	2.12E+02	8.24E+01
Lincoln	3.40E+02	1.02E-05	4.12E+01	5.72E+00	2.24E-01	4.74E-02	1.22E-06	9.58E-06	3.14E-02	2.35E+02	9.14E+01
Manitowoc	1.42E+02	4.28E-06	1.72E+01	2.39E+00	9.37E-02	1.98E-02	5.12E-07	4.01E-06	1.31E-02	9.84E+01	3.83E+01
Marathon	2.88E+02	8.68E-06	3.49E+01	4.85E+00	1.90E-01	4.02E-02	1.04E-06	8.13E-06	2.66E-02	1.99E+02	7.75E+01
Marinette	3.00E+02	9.05E-06	3.64E+01	5.05E+00	1.98E-01	4.19E-02	1.08E-06	8.47E-06	2.77E-02	2.08E+02	8.08E+01
Marquette	2.03E+02	6.11E-06	2.46E+01	3.41E+00	1.34E-01	2.83E-02	7.30E-07	5.72E-06	1.87E-02	1.40E+02	5.46E+01
Milwaukee	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Monroe	2.78E+02	8.38E-06	3.37E+01	4.68E+00	1.83E-01	3.88E-02	1.00E-06	7.84E-06	2.57E-02	1.92E+02	7.48E+01
Oconto	2.78E+02	8.38E-06	3.37E+01	4.68E+00	1.83E-01	3.88E-02	1.00E-06	7.84E-06	2.57E-02	1.92E+02	7.48E+01
Oneida	3.93E+02	1.18E-05	4.76E+01	6.61E+00	2.58E-01	5.47E-02	1.41E-06	1.11E-05	3.62E-02	2.72E+02	1.06E+02
Outagamie	1.83E+02	5.52E-06	2.22E+01	3.08E+00	1.21E-01	2.55E-02	6.59E-07	5.17E-06	1.69E-02	1.27E+02	4.93E+01

Ozaukee	4.60E+01	1.39E-06	5.58E+00	7.75E-01	3.03E-02	6.42E-03	1.66E-07	1.30E-06	4.25E-03	3.19E+01	1.24E+01
Pepin	4.21E+02	1.27E-05	5.10E+01	7.08E+00	2.77E-01	5.86E-02	1.51E-06	1.19E-05	3.88E-02	2.91E+02	1.13E+02
Pierce	4.62E+02	1.39E-05	5.60E+01	7.77E+00	3.04E-01	6.43E-02	1.66E-06	1.30E-05	4.26E-02	3.19E+02	1.24E+02
Polk	5.19E+02	1.56E-05	6.29E+01	8.74E+00	3.42E-01	7.24E-02	1.87E-06	1.46E-05	4.79E-02	3.59E+02	1.40E+02
Portage	2.34E+02	7.05E-06	2.84E+01	3.94E+00	1.54E-01	3.26E-02	8.42E-07	6.60E-06	2.16E-02	1.62E+02	6.29E+01
Price	4.33E+02	1.30E-05	5.25E+01	7.29E+00	2.85E-01	6.04E-02	1.56E-06	1.22E-05	4.00E-02	3.00E+02	1.16E+02
Racine	4.36E+01	1.31E-06	5.28E+00	7.33E-01	2.87E-02	6.08E-03	1.57E-07	1.23E-06	4.02E-03	3.02E+01	1.17E+01
Richland	2.29E+02	6.89E-06	2.77E+01	3.85E+00	1.51E-01	3.19E-02	8.23E-07	6.45E-06	2.11E-02	1.58E+02	6.15E+01
Rock	1.29E+02	3.88E-06	1.56E+01	2.17E+00	8.49E-02	1.80E-02	4.64E-07	3.64E-06	1.19E-02	8.92E+01	3.47E+01
Rusk	4.62E+02	1.39E-05	5.59E+01	7.77E+00	3.04E-01	6.43E-02	1.66E-06	1.30E-05	4.26E-02	3.19E+02	1.24E+02
Saint Croix	4.81E+02	1.45E-05	5.83E+01	8.09E+00	3.17E-01	6.70E-02	1.73E-06	1.36E-05	4.44E-02	3.33E+02	1.29E+02
Sauk	2.05E+02	6.16E-06	2.48E+01	3.44E+00	1.35E-01	2.85E-02	7.36E-07	5.77E-06	1.89E-02	1.41E+02	5.50E+01
Sawyer	5.29E+02	1.59E-05	6.41E+01	8.91E+00	3.48E-01	7.38E-02	1.90E-06	1.49E-05	4.88E-02	3.66E+02	1.42E+02
Shawano	2.45E+02	7.37E-06	2.97E+01	4.12E+00	1.61E-01	3.41E-02	8.81E-07	6.90E-06	2.26E-02	1.69E+02	6.58E+01
Sheboygan	8.41E+01	2.53E-06	1.02E+01	1.41E+00	5.53E-02	1.17E-02	3.02E-07	2.37E-06	7.76E-03	5.82E+01	2.26E+01
Taylor	3.86E+02	1.16E-05	4.68E+01	6.49E+00	2.54E-01	5.38E-02	1.39E-06	1.09E-05	3.56E-02	2.67E+02	1.04E+02
Trempealeau	3.67E+02	1.10E-05	4.44E+01	6.17E+00	2.41E-01	5.11E-02	1.32E-06	1.03E-05	3.38E-02	2.54E+02	9.86E+01
Vernon	2.76E+02	8.30E-06	3.34E+01	4.64E+00	1.81E-01	3.84E-02	9.92E-07	7.77E-06	2.54E-02	1.91E+02	7.41E+01
Vilas	4.37E+02	1.32E-05	5.29E+01	7.35E+00	2.88E-01	6.09E-02	1.57E-06	1.23E-05	4.03E-02	3.02E+02	1.18E+02

Walworth	6.46E+01	1.94E-06	7.82E+00	1.09E+00	4.25E-02	9.00E-03	2.32E-07	1.82E-06	5.96E-03	4.47E+01	1.74E+01
Washburn	5.26E+02	1.58E-05	6.38E+01	8.86E+00	3.47E-01	7.33E-02	1.89E-06	1.48E-05	4.86E-02	3.64E+02	1.42E+02
Washington	5.12E+01	1.54E-06	6.20E+00	8.62E-01	3.37E-02	7.14E-03	1.84E-07	1.44E-06	4.73E-03	3.54E+01	1.38E+01
Waukesha	3.12E+01	9.39E-07	3.78E+00	5.25E-01	2.05E-02	4.34E-03	1.12E-07	8.79E-07	2.88E-03	2.16E+01	8.38E+00
Waupaca	2.09E+02	6.29E-06	2.53E+01	3.52E+00	1.38E-01	2.91E-02	7.52E-07	5.89E-06	1.93E-02	1.45E+02	5.62E+01
Waushara	1.92E+02	5.79E-06	2.33E+01	3.24E+00	1.27E-01	2.68E-02	6.92E-07	5.42E-06	1.77E-02	1.33E+02	5.17E+01
Winnebago	1.49E+02	4.48E-06	1.80E+01	2.50E+00	9.80E-02	2.07E-02	5.35E-07	4.19E-06	1.37E-02	1.03E+02	4.00E+01
Wood	2.87E+02	8.63E-06	3.47E+01	4.82E+00	1.89E-01	3.99E-02	1.03E-06	8.08E-06	2.64E-02	1.98E+02	7.70E+01
Menominee	2.71E+02	8.17E-06	3.29E+01	4.56E+00	1.79E-01	3.78E-02	9.76E-07	7.65E-06	2.50E-02	1.88E+02	7.30E+01

Table E95. County-Level Land Transportation Environmental Impacts (Consumption in Minneapolis).

County	Driving route	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
Unit	km	kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	CTUh	CTUh	kg PM2.5 eq	CTUe	MJ surplus
Adams	3.41E+02	1.03E-05	4.13E+01	5.73E+00	2.24E-01	4.74E-02	1.23E-06	9.60E-06	3.14E-02	2.36E+02	9.16E+01
Ashland	3.11E+02	9.38E-06	3.77E+01	5.24E+00	2.05E-01	4.34E-02	1.12E-06	8.78E-06	2.87E-02	2.15E+02	8.37E+01
Barron	1.48E+02	4.46E-06	1.79E+01	2.49E+00	9.75E-02	2.06E-02	5.33E-07	4.17E-06	1.37E-02	1.02E+02	3.98E+01

Bayfield	3.48E+02	1.05E-05	4.22E+01	5.86E+00	2.29E-01	4.85E-02	1.25E-06	9.81E-06	3.21E-02	2.41E+02	9.36E+01
Brown	4.58E+02	1.38E-05	5.54E+01	7.70E+00	3.01E-01	6.37E-02	1.65E-06	1.29E-05	4.22E-02	3.16E+02	1.23E+02
Buffalo	1.90E+02	5.72E-06	2.30E+01	3.20E+00	1.25E-01	2.65E-02	6.84E-07	5.36E-06	1.75E-02	1.31E+02	5.11E+01
Burnett	1.29E+02	3.89E-06	1.56E+01	2.17E+00	8.50E-02	1.80E-02	4.64E-07	3.64E-06	1.19E-02	8.93E+01	3.47E+01
Calumet	5.09E+02	1.53E-05	6.16E+01	8.56E+00	3.35E-01	7.09E-02	1.83E-06	1.43E-05	4.69E-02	3.52E+02	1.37E+02
Chippewa	1.58E+02	4.75E-06	1.91E+01	2.65E+00	1.04E-01	2.20E-02	5.67E-07	4.45E-06	1.46E-02	1.09E+02	4.24E+01
Clark	2.48E+02	7.45E-06	3.00E+01	4.16E+00	1.63E-01	3.45E-02	8.91E-07	6.98E-06	2.28E-02	1.71E+02	6.65E+01
Columbia	3.97E+02	1.19E-05	4.80E+01	6.67E+00	2.61E-01	5.52E-02	1.43E-06	1.12E-05	3.66E-02	2.74E+02	1.07E+02
Crawford	3.40E+02	1.02E-05	4.12E+01	5.71E+00	2.24E-01	4.73E-02	1.22E-06	9.57E-06	3.13E-02	2.35E+02	9.13E+01
Dane	4.34E+02	1.31E-05	5.26E+01	7.30E+00	2.86E-01	6.05E-02	1.56E-06	1.22E-05	4.01E-02	3.00E+02	1.17E+02
Dodge	4.60E+02	1.38E-05	5.57E+01	7.73E+00	3.03E-01	6.40E-02	1.65E-06	1.30E-05	4.24E-02	3.18E+02	1.24E+02
Door	5.04E+02	1.52E-05	6.11E+01	8.49E+00	3.32E-01	7.03E-02	1.81E-06	1.42E-05	4.65E-02	3.49E+02	1.36E+02
Douglas	2.49E+02	7.48E-06	3.01E+01	4.18E+00	1.64E-01	3.46E-02	8.94E-07	7.01E-06	2.29E-02	1.72E+02	6.68E+01
Dunn	1.28E+02	3.86E-06	1.55E+01	2.16E+00	8.43E-02	1.79E-02	4.61E-07	3.61E-06	1.18E-02	8.86E+01	3.44E+01
Eau Claire	1.48E+02	4.46E-06	1.80E+01	2.49E+00	9.76E-02	2.07E-02	5.33E-07	4.18E-06	1.37E-02	1.03E+02	3.99E+01
Florence	4.80E+02	1.44E-05	5.81E+01	8.07E+00	3.16E-01	6.68E-02	1.73E-06	1.35E-05	4.42E-02	3.32E+02	1.29E+02
Fond du Lac	4.89E+02	1.47E-05	5.93E+01	8.23E+00	3.22E-01	6.82E-02	1.76E-06	1.38E-05	4.51E-02	3.38E+02	1.32E+02
Forest	4.46E+02	1.34E-05	5.40E+01	7.49E+00	2.93E-01	6.21E-02	1.60E-06	1.26E-05	4.11E-02	3.08E+02	1.20E+02
Grant	3.99E+02	1.20E-05	4.84E+01	6.72E+00	2.63E-01	5.56E-02	1.44E-06	1.13E-05	3.68E-02	2.76E+02	1.07E+02

Green	4.72E+02	1.42E-05	5.71E+01	7.93E+00	3.10E-01	6.57E-02	1.70E-06	1.33E-05	4.35E-02	3.26E+02	1.27E+02
Green Lake	4.07E+02	1.22E-05	4.93E+01	6.84E+00	2.68E-01	5.67E-02	1.46E-06	1.15E-05	3.75E-02	2.81E+02	1.09E+02
Iowa	4.26E+02	1.28E-05	5.16E+01	7.17E+00	2.80E-01	5.94E-02	1.53E-06	1.20E-05	3.93E-02	2.95E+02	1.15E+02
Iron	3.74E+02	1.13E-05	4.54E+01	6.30E+00	2.46E-01	5.22E-02	1.35E-06	1.06E-05	3.45E-02	2.59E+02	1.01E+02
Jackson	2.31E+02	6.96E-06	2.80E+01	3.89E+00	1.52E-01	3.22E-02	8.32E-07	6.52E-06	2.13E-02	1.60E+02	6.22E+01
Jefferson	4.78E+02	1.44E-05	5.79E+01	8.04E+00	3.15E-01	6.66E-02	1.72E-06	1.35E-05	4.41E-02	3.31E+02	1.29E+02
Juneau	3.13E+02	9.41E-06	3.79E+01	5.26E+00	2.06E-01	4.36E-02	1.12E-06	8.81E-06	2.88E-02	2.16E+02	8.40E+01
Kenosha	6.02E+02	1.81E-05	7.29E+01	1.01E+01	3.96E-01	8.39E-02	2.17E-06	1.70E-05	5.55E-02	4.16E+02	1.62E+02
Kewaunee	4.97E+02	1.50E-05	6.03E+01	8.37E+00	3.27E-01	6.93E-02	1.79E-06	1.40E-05	4.59E-02	3.44E+02	1.34E+02
La Crosse	2.51E+02	7.55E-06	3.04E+01	4.22E+00	1.65E-01	3.49E-02	9.02E-07	7.07E-06	2.31E-02	1.74E+02	6.74E+01
Lafayette	4.65E+02	1.40E-05	5.64E+01	7.83E+00	3.06E-01	6.49E-02	1.67E-06	1.31E-05	4.29E-02	3.22E+02	1.25E+02
Langlade	3.72E+02	1.12E-05	4.51E+01	6.26E+00	2.45E-01	5.19E-02	1.34E-06	1.05E-05	3.43E-02	2.57E+02	1.00E+02
Lincoln	3.42E+02	1.03E-05	4.14E+01	5.75E+00	2.25E-01	4.76E-02	1.23E-06	9.63E-06	3.15E-02	2.36E+02	9.18E+01
Manitowoc	5.13E+02	1.54E-05	6.21E+01	8.63E+00	3.38E-01	7.15E-02	1.85E-06	1.45E-05	4.73E-02	3.55E+02	1.38E+02
Marathon	2.92E+02	8.80E-06	3.54E+01	4.92E+00	1.93E-01	4.07E-02	1.05E-06	8.24E-06	2.70E-02	2.02E+02	7.86E+01
Marinette	4.66E+02	1.40E-05	5.65E+01	7.84E+00	3.07E-01	6.49E-02	1.68E-06	1.31E-05	4.30E-02	3.22E+02	1.25E+02
Marquette	3.73E+02	1.12E-05	4.52E+01	6.28E+00	2.46E-01	5.20E-02	1.34E-06	1.05E-05	3.44E-02	2.58E+02	1.00E+02
Milwaukee	5.37E+02	1.62E-05	6.51E+01	9.04E+00	3.54E-01	7.49E-02	1.93E-06	1.51E-05	4.96E-02	3.72E+02	1.44E+02
Monroe	2.91E+02	8.75E-06	3.52E+01	4.89E+00	1.91E-01	4.05E-02	1.05E-06	8.19E-06	2.68E-02	2.01E+02	7.81E+01

Oconto	4.39E+02	1.32E-05	5.32E+01	7.38E+00	2.89E-01	6.11E-02	1.58E-06	1.24E-05	4.05E-02	3.04E+02	1.18E+02
Oneida	3.94E+02	1.19E-05	4.78E+01	6.63E+00	2.60E-01	5.49E-02	1.42E-06	1.11E-05	3.64E-02	2.73E+02	1.06E+02
Outagamie	4.39E+02	1.32E-05	5.31E+01	7.38E+00	2.89E-01	6.11E-02	1.58E-06	1.24E-05	4.05E-02	3.03E+02	1.18E+02
Ozaukee	5.21E+02	1.57E-05	6.31E+01	8.76E+00	3.43E-01	7.25E-02	1.87E-06	1.47E-05	4.80E-02	3.60E+02	1.40E+02
Pepin	1.23E+02	3.70E-06	1.49E+01	2.06E+00	8.08E-02	1.71E-02	4.42E-07	3.46E-06	1.13E-02	8.49E+01	3.30E+01
Pierce	8.93E+01	2.69E-06	1.08E+01	1.50E+00	5.88E-02	1.24E-02	3.21E-07	2.52E-06	8.24E-03	6.17E+01	2.40E+01
Polk	1.06E+02	3.18E-06	1.28E+01	1.78E+00	6.96E-02	1.47E-02	3.80E-07	2.98E-06	9.75E-03	7.31E+01	2.84E+01
Portage	3.58E+02	1.08E-05	4.33E+01	6.02E+00	2.35E-01	4.98E-02	1.29E-06	1.01E-05	3.30E-02	2.47E+02	9.62E+01
Price	2.81E+02	8.47E-06	3.41E+01	4.73E+00	1.85E-01	3.92E-02	1.01E-06	7.93E-06	2.60E-02	1.95E+02	7.56E+01
Racine	5.80E+02	1.75E-05	7.02E+01	9.75E+00	3.82E-01	8.08E-02	2.09E-06	1.63E-05	5.35E-02	4.01E+02	1.56E+02
Richland	3.50E+02	1.05E-05	4.24E+01	5.89E+00	2.31E-01	4.88E-02	1.26E-06	9.88E-06	3.23E-02	2.42E+02	9.42E+01
Rock	5.01E+02	1.51E-05	6.07E+01	8.43E+00	3.30E-01	6.98E-02	1.80E-06	1.41E-05	4.62E-02	3.47E+02	1.35E+02
Rusk	2.06E+02	6.21E-06	2.50E+01	3.47E+00	1.36E-01	2.87E-02	7.42E-07	5.81E-06	1.90E-02	1.43E+02	5.55E+01
Saint Croix	7.39E+01	2.22E-06	8.95E+00	1.24E+00	4.86E-02	1.03E-02	2.66E-07	2.08E-06	6.82E-03	5.11E+01	1.99E+01
Sauk	3.83E+02	1.15E-05	4.64E+01	6.44E+00	2.52E-01	5.33E-02	1.38E-06	1.08E-05	3.53E-02	2.65E+02	1.03E+02
Sawyer	2.41E+02	7.25E-06	2.92E+01	4.05E+00	1.59E-01	3.36E-02	8.67E-07	6.79E-06	2.22E-02	1.67E+02	6.48E+01
Shawano	3.81E+02	1.15E-05	4.61E+01	6.41E+00	2.51E-01	5.31E-02	1.37E-06	1.07E-05	3.51E-02	2.63E+02	1.02E+02
Sheboygan	5.35E+02	1.61E-05	6.48E+01	9.00E+00	3.52E-01	7.45E-02	1.92E-06	1.51E-05	4.94E-02	3.70E+02	1.44E+02
Taylor	2.64E+02	7.95E-06	3.20E+01	4.44E+00	1.74E-01	3.68E-02	9.50E-07	7.44E-06	2.44E-02	1.83E+02	7.10E+01

Trempealeau	2.33E+02	7.02E-06	2.83E+01	3.92E+00	1.54E-01	3.25E-02	8.39E-07	6.57E-06	2.15E-02	1.61E+02	6.27E+01
Vernon	3.06E+02	9.21E-06	3.71E+01	5.15E+00	2.01E-01	4.26E-02	1.10E-06	8.62E-06	2.82E-02	2.12E+02	8.23E+01
Vilas	4.39E+02	1.32E-05	5.31E+01	7.38E+00	2.89E-01	6.11E-02	1.58E-06	1.24E-05	4.05E-02	3.03E+02	1.18E+02
Walworth	5.23E+02	1.58E-05	6.34E+01	8.80E+00	3.45E-01	7.29E-02	1.88E-06	1.48E-05	4.83E-02	3.62E+02	1.41E+02
Washburn	1.90E+02	5.73E-06	2.30E+01	3.20E+00	1.25E-01	2.65E-02	6.85E-07	5.36E-06	1.76E-02	1.32E+02	5.12E+01
Washington	5.04E+02	1.52E-05	6.10E+01	8.48E+00	3.32E-01	7.02E-02	1.81E-06	1.42E-05	4.65E-02	3.49E+02	1.35E+02
Waukesha	5.09E+02	1.53E-05	6.17E+01	8.57E+00	3.35E-01	7.10E-02	1.83E-06	1.44E-05	4.70E-02	3.52E+02	1.37E+02
Waupaca	3.97E+02	1.20E-05	4.81E+01	6.68E+00	2.62E-01	5.54E-02	1.43E-06	1.12E-05	3.67E-02	2.75E+02	1.07E+02
Waushara	3.85E+02	1.16E-05	4.66E+01	6.48E+00	2.53E-01	5.36E-02	1.39E-06	1.09E-05	3.55E-02	2.66E+02	1.03E+02
Winnebago	4.32E+02	1.30E-05	5.23E+01	7.27E+00	2.84E-01	6.02E-02	1.55E-06	1.22E-05	3.99E-02	2.99E+02	1.16E+02
Wood	2.89E+02	8.70E-06	3.50E+01	4.86E+00	1.90E-01	4.03E-02	1.04E-06	8.15E-06	2.67E-02	2.00E+02	7.77E+01
Menominee	3.86E+02	1.16E-05	4.68E+01	6.49E+00	2.54E-01	5.38E-02	1.39E-06	1.09E-05	3.56E-02	2.67E+02	1.04E+02

Table E96. County-Level Space Heating Environmental Impacts (Ineffective Space Heating, SC1).

County	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
Unit	kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	CTUh	CTUh	kg PM2.5 eq	CTUe	MJ surplus

Adams	1.37E-13	1.91E-01	4.19E-03	1.64E-03	1.61E-05	8.07E-10	1.01E-08	9.62E-05	2.56E-01	5.01E-01
Ashland	1.53E-13	2.14E-01	4.68E-03	1.83E-03	1.80E-05	9.02E-10	1.13E-08	1.08E-04	2.86E-01	5.60E-01
Barron	1.46E-13	2.04E-01	4.47E-03	1.75E-03	1.72E-05	8.61E-10	1.07E-08	1.03E-04	2.73E-01	5.34E-01
Bayfield	1.53E-13	2.14E-01	4.68E-03	1.83E-03	1.80E-05	9.02E-10	1.13E-08	1.08E-04	2.86E-01	5.60E-01
Brown	1.32E-13	1.84E-01	4.03E-03	1.57E-03	1.55E-05	7.76E-10	9.68E-09	9.25E-05	2.46E-01	4.81E-01
Buffalo	1.40E-13	1.96E-01	4.29E-03	1.68E-03	1.65E-05	8.26E-10	1.03E-08	9.85E-05	2.62E-01	5.13E-01
Burnett	1.48E-13	2.07E-01	4.52E-03	1.77E-03	1.74E-05	8.71E-10	1.09E-08	1.04E-04	2.76E-01	5.40E-01
Calumet	1.31E-13	1.83E-01	4.01E-03	1.57E-03	1.54E-05	7.73E-10	9.65E-09	9.21E-05	2.45E-01	4.80E-01
Chippewa	1.40E-13	1.96E-01	4.29E-03	1.68E-03	1.65E-05	8.26E-10	1.03E-08	9.85E-05	2.62E-01	5.13E-01
Clark	1.43E-13	1.99E-01	4.36E-03	1.70E-03	1.68E-05	8.40E-10	1.05E-08	1.00E-04	2.66E-01	5.21E-01
Columbia	1.36E-13	1.91E-01	4.17E-03	1.63E-03	1.60E-05	8.03E-10	1.00E-08	9.57E-05	2.55E-01	4.98E-01
Crawford	1.24E-13	1.73E-01	3.79E-03	1.48E-03	1.46E-05	7.30E-10	9.11E-09	8.70E-05	2.31E-01	4.53E-01
Dane	1.27E-13	1.77E-01	3.87E-03	1.51E-03	1.49E-05	7.46E-10	9.31E-09	8.89E-05	2.37E-01	4.63E-01
Dodge	1.30E-13	1.82E-01	3.98E-03	1.55E-03	1.53E-05	7.67E-10	9.57E-09	9.14E-05	2.43E-01	4.76E-01
Door	1.32E-13	1.84E-01	4.03E-03	1.57E-03	1.55E-05	7.76E-10	9.68E-09	9.25E-05	2.46E-01	4.81E-01
Douglas	1.54E-13	2.15E-01	4.71E-03	1.84E-03	1.81E-05	9.07E-10	1.13E-08	1.08E-04	2.88E-01	5.63E-01
Dunn	1.40E-13	1.96E-01	4.29E-03	1.68E-03	1.65E-05	8.26E-10	1.03E-08	9.85E-05	2.62E-01	5.13E-01
Eau Claire	1.40E-13	1.96E-01	4.29E-03	1.68E-03	1.65E-05	8.26E-10	1.03E-08	9.85E-05	2.62E-01	5.13E-01
Florence	1.48E-13	2.07E-01	4.53E-03	1.77E-03	1.74E-05	8.72E-10	1.09E-08	1.04E-04	2.77E-01	5.41E-01

Fond du Lac	1.29E-13	1.80E-01	3.94E-03	1.54E-03	1.52E-05	7.59E-10	9.47E-09	9.05E-05	2.41E-01	4.71E-01
Forest	1.57E-13	2.20E-01	4.80E-03	1.88E-03	1.85E-05	9.26E-10	1.16E-08	1.10E-04	2.94E-01	5.74E-01
Grant	1.24E-13	1.73E-01	3.79E-03	1.48E-03	1.46E-05	7.30E-10	9.11E-09	8.70E-05	2.31E-01	4.53E-01
Green	1.24E-13	1.73E-01	3.78E-03	1.48E-03	1.46E-05	7.29E-10	9.10E-09	8.69E-05	2.31E-01	4.53E-01
Green Lake	1.31E-13	1.83E-01	4.01E-03	1.57E-03	1.54E-05	7.73E-10	9.65E-09	9.21E-05	2.45E-01	4.80E-01
Iowa	1.24E-13	1.73E-01	3.79E-03	1.48E-03	1.46E-05	7.30E-10	9.11E-09	8.70E-05	2.31E-01	4.53E-01
Iron	1.53E-13	2.14E-01	4.68E-03	1.83E-03	1.80E-05	9.02E-10	1.13E-08	1.08E-04	2.86E-01	5.60E-01
Jackson	1.42E-13	1.98E-01	4.34E-03	1.70E-03	1.67E-05	8.36E-10	1.04E-08	9.97E-05	2.65E-01	5.19E-01
Jefferson	1.34E-13	1.87E-01	4.10E-03	1.60E-03	1.58E-05	7.90E-10	9.86E-09	9.42E-05	2.51E-01	4.90E-01
Juneau	1.42E-13	1.98E-01	4.34E-03	1.70E-03	1.67E-05	8.36E-10	1.04E-08	9.97E-05	2.65E-01	5.19E-01
Kenosha	1.20E-13	1.67E-01	3.66E-03	1.43E-03	1.41E-05	7.06E-10	8.81E-09	8.41E-05	2.24E-01	4.38E-01
Kewaunee	1.32E-13	1.84E-01	4.03E-03	1.57E-03	1.55E-05	7.76E-10	9.68E-09	9.25E-05	2.46E-01	4.81E-01
La Crosse	1.24E-13	1.73E-01	3.78E-03	1.48E-03	1.46E-05	7.29E-10	9.10E-09	8.69E-05	2.31E-01	4.52E-01
Lafayette	1.24E-13	1.73E-01	3.78E-03	1.48E-03	1.46E-05	7.29E-10	9.10E-09	8.69E-05	2.31E-01	4.53E-01
Langlade	1.48E-13	2.07E-01	4.53E-03	1.77E-03	1.74E-05	8.73E-10	1.09E-08	1.04E-04	2.77E-01	5.42E-01
Lincoln	1.48E-13	2.07E-01	4.53E-03	1.77E-03	1.74E-05	8.73E-10	1.09E-08	1.04E-04	2.77E-01	5.42E-01
Manitowoc	1.34E-13	1.86E-01	4.08E-03	1.59E-03	1.57E-05	7.86E-10	9.81E-09	9.37E-05	2.49E-01	4.88E-01
Marathon	1.44E-13	2.01E-01	4.39E-03	1.71E-03	1.69E-05	8.45E-10	1.06E-08	1.01E-04	2.68E-01	5.25E-01
Marinette	1.48E-13	2.07E-01	4.53E-03	1.77E-03	1.74E-05	8.72E-10	1.09E-08	1.04E-04	2.77E-01	5.41E-01

Marquette	1.37E-13	1.91E-01	4.19E-03	1.64E-03	1.61E-05	8.07E-10	1.01E-08	9.62E-05	2.56E-01	5.01E-01
Milwaukee	1.19E-13	1.66E-01	3.64E-03	1.42E-03	1.40E-05	7.01E-10	8.76E-09	8.36E-05	2.22E-01	4.35E-01
Monroe	1.24E-13	1.73E-01	3.78E-03	1.48E-03	1.46E-05	7.29E-10	9.10E-09	8.69E-05	2.31E-01	4.53E-01
Oconto	1.32E-13	1.84E-01	4.03E-03	1.57E-03	1.55E-05	7.76E-10	9.68E-09	9.25E-05	2.46E-01	4.81E-01
Oneida	1.48E-13	2.07E-01	4.53E-03	1.77E-03	1.74E-05	8.73E-10	1.09E-08	1.04E-04	2.77E-01	5.42E-01
Outagamie	1.35E-13	1.89E-01	4.13E-03	1.61E-03	1.59E-05	7.96E-10	9.94E-09	9.49E-05	2.52E-01	4.94E-01
Ozaukee	1.34E-13	1.86E-01	4.08E-03	1.59E-03	1.57E-05	7.86E-10	9.81E-09	9.37E-05	2.49E-01	4.88E-01
Pepin	1.35E-13	1.88E-01	4.12E-03	1.61E-03	1.59E-05	7.94E-10	9.91E-09	9.46E-05	2.52E-01	4.93E-01
Pierce	1.35E-13	1.88E-01	4.12E-03	1.61E-03	1.59E-05	7.94E-10	9.91E-09	9.46E-05	2.52E-01	4.93E-01
Polk	1.43E-13	1.99E-01	4.35E-03	1.70E-03	1.68E-05	8.39E-10	1.05E-08	1.00E-04	2.66E-01	5.21E-01
Portage	1.49E-13	2.07E-01	4.54E-03	1.77E-03	1.75E-05	8.75E-10	1.09E-08	1.04E-04	2.77E-01	5.43E-01
Price	1.56E-13	2.17E-01	4.76E-03	1.86E-03	1.83E-05	9.17E-10	1.14E-08	1.09E-04	2.91E-01	5.69E-01
Racine	1.22E-13	1.71E-01	3.73E-03	1.46E-03	1.44E-05	7.19E-10	8.98E-09	8.57E-05	2.28E-01	4.46E-01
Richland	1.24E-13	1.73E-01	3.79E-03	1.48E-03	1.46E-05	7.30E-10	9.11E-09	8.70E-05	2.31E-01	4.53E-01
Rock	1.19E-13	1.66E-01	3.64E-03	1.42E-03	1.40E-05	7.01E-10	8.76E-09	8.36E-05	2.22E-01	4.35E-01
Rusk	1.46E-13	2.04E-01	4.47E-03	1.75E-03	1.72E-05	8.61E-10	1.07E-08	1.03E-04	2.73E-01	5.34E-01
Saint Croix	1.44E-13	2.01E-01	4.41E-03	1.72E-03	1.70E-05	8.49E-10	1.06E-08	1.01E-04	2.69E-01	5.27E-01
Sauk	1.24E-13	1.73E-01	3.79E-03	1.48E-03	1.46E-05	7.30E-10	9.11E-09	8.70E-05	2.31E-01	4.53E-01
Sawyer	1.52E-13	2.12E-01	4.63E-03	1.81E-03	1.78E-05	8.92E-10	1.11E-08	1.06E-04	2.83E-01	5.53E-01

Shawano	1.32E-13	1.84E-01	4.03E-03	1.57E-03	1.55E-05	7.76E-10	9.68E-09	9.25E-05	2.46E-01	4.81E-01
Sheboygan	1.34E-13	1.86E-01	4.08E-03	1.59E-03	1.57E-05	7.86E-10	9.81E-09	9.37E-05	2.49E-01	4.88E-01
Taylor	1.55E-13	2.16E-01	4.73E-03	1.85E-03	1.82E-05	9.11E-10	1.14E-08	1.09E-04	2.89E-01	5.66E-01
Trempealeau	1.24E-13	1.73E-01	3.78E-03	1.48E-03	1.46E-05	7.29E-10	9.10E-09	8.69E-05	2.31E-01	4.52E-01
Vernon	1.42E-13	1.98E-01	4.34E-03	1.70E-03	1.67E-05	8.36E-10	1.04E-08	9.97E-05	2.65E-01	5.19E-01
Vilas	1.48E-13	2.07E-01	4.53E-03	1.77E-03	1.75E-05	8.74E-10	1.09E-08	1.04E-04	2.77E-01	5.42E-01
Walworth	1.19E-13	1.66E-01	3.64E-03	1.42E-03	1.40E-05	7.01E-10	8.76E-09	8.36E-05	2.22E-01	4.35E-01
Washburn	1.52E-13	2.12E-01	4.63E-03	1.81E-03	1.78E-05	8.92E-10	1.11E-08	1.06E-04	2.83E-01	5.53E-01
Washington	1.33E-13	1.86E-01	4.07E-03	1.59E-03	1.57E-05	7.85E-10	9.80E-09	9.36E-05	2.49E-01	4.87E-01
Waukesha	1.34E-13	1.87E-01	4.10E-03	1.60E-03	1.58E-05	7.90E-10	9.86E-09	9.42E-05	2.51E-01	4.90E-01
Waupaca	1.28E-13	1.79E-01	3.92E-03	1.53E-03	1.51E-05	7.55E-10	9.43E-09	9.00E-05	2.39E-01	4.69E-01
Waushara	1.28E-13	1.79E-01	3.92E-03	1.53E-03	1.51E-05	7.55E-10	9.43E-09	9.00E-05	2.39E-01	4.69E-01
Winnebago	1.31E-13	1.83E-01	4.01E-03	1.57E-03	1.54E-05	7.73E-10	9.65E-09	9.21E-05	2.45E-01	4.80E-01
Wood	1.37E-13	1.91E-01	4.19E-03	1.64E-03	1.61E-05	8.07E-10	1.01E-08	9.62E-05	2.56E-01	5.01E-01
Menominee	1.55E-13	2.16E-01	4.73E-03	1.85E-03	1.82E-05	9.12E-10	1.14E-08	1.09E-04	2.89E-01	5.66E-01

Table E97. County-Level Space Heating Environmental Impacts (semi-effective Space Heating, SC2).

County	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
Unit	kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	CTUh	CTUh	kg PM2.5 eq	CTUe	MJ surplus
Adams	1.27E-14	1.77E-02	3.88E-04	1.51E-04	1.49E-06	7.47E-11	9.33E-10	8.91E-06	2.37E-02	4.64E-02
Ashland	1.42E-14	1.98E-02	4.33E-04	1.69E-04	1.67E-06	8.35E-11	1.04E-09	9.96E-06	2.65E-02	5.18E-02
Barron	1.35E-14	1.89E-02	4.14E-04	1.62E-04	1.59E-06	7.97E-11	9.95E-10	9.50E-06	2.53E-02	4.95E-02
Bayfield	1.42E-14	1.98E-02	4.33E-04	1.69E-04	1.67E-06	8.35E-11	1.04E-09	9.96E-06	2.65E-02	5.18E-02
Brown	1.22E-14	1.70E-02	3.73E-04	1.46E-04	1.44E-06	7.18E-11	8.97E-10	8.56E-06	2.28E-02	4.46E-02
Buffalo	1.30E-14	1.81E-02	3.97E-04	1.55E-04	1.53E-06	7.65E-11	9.55E-10	9.12E-06	2.43E-02	4.75E-02
Burnett	1.37E-14	1.91E-02	4.18E-04	1.63E-04	1.61E-06	8.06E-11	1.01E-09	9.61E-06	2.56E-02	5.00E-02
Calumet	1.22E-14	1.70E-02	3.71E-04	1.45E-04	1.43E-06	7.16E-11	8.93E-10	8.53E-06	2.27E-02	4.44E-02
Chippewa	1.30E-14	1.81E-02	3.97E-04	1.55E-04	1.53E-06	7.65E-11	9.55E-10	9.12E-06	2.43E-02	4.75E-02
Clark	1.32E-14	1.84E-02	4.03E-04	1.58E-04	1.55E-06	7.78E-11	9.71E-10	9.27E-06	2.47E-02	4.82E-02
Columbia	1.26E-14	1.76E-02	3.86E-04	1.51E-04	1.49E-06	7.44E-11	9.28E-10	8.86E-06	2.36E-02	4.61E-02
Crawford	1.15E-14	1.60E-02	3.51E-04	1.37E-04	1.35E-06	6.76E-11	8.44E-10	8.05E-06	2.14E-02	4.19E-02
Dane	1.17E-14	1.64E-02	3.58E-04	1.40E-04	1.38E-06	6.91E-11	8.62E-10	8.23E-06	2.19E-02	4.28E-02
Dodge	1.21E-14	1.68E-02	3.68E-04	1.44E-04	1.42E-06	7.10E-11	8.86E-10	8.46E-06	2.25E-02	4.41E-02
Door	1.22E-14	1.70E-02	3.73E-04	1.46E-04	1.44E-06	7.18E-11	8.97E-10	8.56E-06	2.28E-02	4.46E-02
Douglas	1.43E-14	1.99E-02	4.36E-04	1.70E-04	1.68E-06	8.40E-11	1.05E-09	1.00E-05	2.66E-02	5.21E-02

Dunn	1.30E-14	1.81E-02	3.97E-04	1.55E-04	1.53E-06	7.65E-11	9.55E-10	9.12E-06	2.43E-02	4.75E-02
Eau Claire	1.30E-14	1.81E-02	3.97E-04	1.55E-04	1.53E-06	7.65E-11	9.55E-10	9.12E-06	2.43E-02	4.75E-02
Florence	1.37E-14	1.92E-02	4.19E-04	1.64E-04	1.61E-06	8.08E-11	1.01E-09	9.63E-06	2.56E-02	5.01E-02
Fond du Lac	1.19E-14	1.67E-02	3.65E-04	1.42E-04	1.40E-06	7.03E-11	8.77E-10	8.38E-06	2.23E-02	4.36E-02
Forest	1.46E-14	2.03E-02	4.45E-04	1.74E-04	1.71E-06	8.57E-11	1.07E-09	1.02E-05	2.72E-02	5.32E-02
Grant	1.15E-14	1.60E-02	3.51E-04	1.37E-04	1.35E-06	6.76E-11	8.44E-10	8.05E-06	2.14E-02	4.19E-02
Green	1.15E-14	1.60E-02	3.50E-04	1.37E-04	1.35E-06	6.75E-11	8.43E-10	8.05E-06	2.14E-02	4.19E-02
Green Lake	1.22E-14	1.70E-02	3.71E-04	1.45E-04	1.43E-06	7.16E-11	8.93E-10	8.53E-06	2.27E-02	4.44E-02
Iowa	1.15E-14	1.60E-02	3.51E-04	1.37E-04	1.35E-06	6.76E-11	8.44E-10	8.05E-06	2.14E-02	4.19E-02
Iron	1.42E-14	1.98E-02	4.33E-04	1.69E-04	1.67E-06	8.35E-11	1.04E-09	9.96E-06	2.65E-02	5.18E-02
Jackson	1.32E-14	1.84E-02	4.02E-04	1.57E-04	1.55E-06	7.74E-11	9.67E-10	9.23E-06	2.46E-02	4.80E-02
Jefferson	1.24E-14	1.74E-02	3.80E-04	1.48E-04	1.46E-06	7.32E-11	9.13E-10	8.72E-06	2.32E-02	4.54E-02
Juneau	1.32E-14	1.84E-02	4.02E-04	1.57E-04	1.55E-06	7.74E-11	9.67E-10	9.23E-06	2.46E-02	4.80E-02
Kenosha	1.11E-14	1.55E-02	3.39E-04	1.32E-04	1.31E-06	6.53E-11	8.16E-10	7.79E-06	2.07E-02	4.05E-02
Kewaunee	1.22E-14	1.70E-02	3.73E-04	1.46E-04	1.44E-06	7.18E-11	8.97E-10	8.56E-06	2.28E-02	4.46E-02
La Crosse	1.15E-14	1.60E-02	3.50E-04	1.37E-04	1.35E-06	6.75E-11	8.42E-10	8.04E-06	2.14E-02	4.19E-02
Lafayette	1.15E-14	1.60E-02	3.50E-04	1.37E-04	1.35E-06	6.75E-11	8.43E-10	8.05E-06	2.14E-02	4.19E-02
Langlade	1.37E-14	1.92E-02	4.19E-04	1.64E-04	1.62E-06	8.08E-11	1.01E-09	9.63E-06	2.56E-02	5.02E-02
Lincoln	1.37E-14	1.92E-02	4.19E-04	1.64E-04	1.62E-06	8.08E-11	1.01E-09	9.63E-06	2.56E-02	5.02E-02

Manitowoc	1.24E-14	1.73E-02	3.78E-04	1.48E-04	1.45E-06	7.28E-11	9.08E-10	8.67E-06	2.31E-02	4.52E-02
Marathon	1.33E-14	1.86E-02	4.06E-04	1.59E-04	1.56E-06	7.83E-11	9.77E-10	9.33E-06	2.48E-02	4.86E-02
Marinette	1.37E-14	1.92E-02	4.19E-04	1.64E-04	1.61E-06	8.08E-11	1.01E-09	9.63E-06	2.56E-02	5.01E-02
Marquette	1.27E-14	1.77E-02	3.88E-04	1.51E-04	1.49E-06	7.47E-11	9.33E-10	8.91E-06	2.37E-02	4.64E-02
Milwaukee	1.10E-14	1.54E-02	3.37E-04	1.32E-04	1.30E-06	6.49E-11	8.11E-10	7.74E-06	2.06E-02	4.03E-02
Monroe	1.15E-14	1.60E-02	3.50E-04	1.37E-04	1.35E-06	6.75E-11	8.43E-10	8.05E-06	2.14E-02	4.19E-02
Oconto	1.22E-14	1.70E-02	3.73E-04	1.46E-04	1.44E-06	7.18E-11	8.97E-10	8.56E-06	2.28E-02	4.46E-02
Oneida	1.37E-14	1.92E-02	4.19E-04	1.64E-04	1.62E-06	8.08E-11	1.01E-09	9.63E-06	2.56E-02	5.02E-02
Outagamie	1.25E-14	1.75E-02	3.82E-04	1.49E-04	1.47E-06	7.37E-11	9.20E-10	8.78E-06	2.34E-02	4.57E-02
Ozaukee	1.24E-14	1.73E-02	3.78E-04	1.48E-04	1.45E-06	7.28E-11	9.08E-10	8.67E-06	2.31E-02	4.52E-02
Pepin	1.25E-14	1.74E-02	3.81E-04	1.49E-04	1.47E-06	7.35E-11	9.18E-10	8.76E-06	2.33E-02	4.56E-02
Pierce	1.25E-14	1.74E-02	3.81E-04	1.49E-04	1.47E-06	7.35E-11	9.18E-10	8.76E-06	2.33E-02	4.56E-02
Polk	1.32E-14	1.84E-02	4.03E-04	1.57E-04	1.55E-06	7.77E-11	9.70E-10	9.26E-06	2.46E-02	4.82E-02
Portage	1.38E-14	1.92E-02	4.20E-04	1.64E-04	1.62E-06	8.10E-11	1.01E-09	9.65E-06	2.57E-02	5.03E-02
Price	1.44E-14	2.01E-02	4.40E-04	1.72E-04	1.70E-06	8.49E-11	1.06E-09	1.01E-05	2.69E-02	5.27E-02
Racine	1.13E-14	1.58E-02	3.46E-04	1.35E-04	1.33E-06	6.66E-11	8.31E-10	7.94E-06	2.11E-02	4.13E-02
Richland	1.15E-14	1.60E-02	3.51E-04	1.37E-04	1.35E-06	6.76E-11	8.44E-10	8.05E-06	2.14E-02	4.19E-02
Rock	1.10E-14	1.54E-02	3.37E-04	1.32E-04	1.30E-06	6.50E-11	8.11E-10	7.74E-06	2.06E-02	4.03E-02
Rusk	1.35E-14	1.89E-02	4.14E-04	1.62E-04	1.59E-06	7.97E-11	9.95E-10	9.50E-06	2.53E-02	4.95E-02

Saint Croix	1.34E-14	1.86E-02	4.08E-04	1.59E-04	1.57E-06	7.86E-11	9.81E-10	9.37E-06	2.49E-02	4.88E-02
Sauk	1.15E-14	1.60E-02	3.51E-04	1.37E-04	1.35E-06	6.76E-11	8.44E-10	8.05E-06	2.14E-02	4.19E-02
Sawyer	1.40E-14	1.96E-02	4.29E-04	1.67E-04	1.65E-06	8.26E-11	1.03E-09	9.84E-06	2.62E-02	5.12E-02
Shawano	1.22E-14	1.70E-02	3.73E-04	1.46E-04	1.44E-06	7.18E-11	8.97E-10	8.56E-06	2.28E-02	4.46E-02
Sheboygan	1.24E-14	1.73E-02	3.78E-04	1.48E-04	1.45E-06	7.28E-11	9.08E-10	8.67E-06	2.31E-02	4.52E-02
Taylor	1.43E-14	2.00E-02	4.38E-04	1.71E-04	1.69E-06	8.44E-11	1.05E-09	1.01E-05	2.68E-02	5.24E-02
Trempealeau	1.15E-14	1.60E-02	3.50E-04	1.37E-04	1.35E-06	6.75E-11	8.42E-10	8.04E-06	2.14E-02	4.19E-02
Vernon	1.32E-14	1.84E-02	4.02E-04	1.57E-04	1.55E-06	7.74E-11	9.67E-10	9.23E-06	2.46E-02	4.80E-02
Vilas	1.37E-14	1.92E-02	4.20E-04	1.64E-04	1.62E-06	8.09E-11	1.01E-09	9.64E-06	2.57E-02	5.02E-02
Walworth	1.10E-14	1.54E-02	3.37E-04	1.32E-04	1.30E-06	6.50E-11	8.11E-10	7.74E-06	2.06E-02	4.03E-02
Washburn	1.40E-14	1.96E-02	4.29E-04	1.67E-04	1.65E-06	8.26E-11	1.03E-09	9.84E-06	2.62E-02	5.12E-02
Washington	1.24E-14	1.72E-02	3.77E-04	1.47E-04	1.45E-06	7.27E-11	9.07E-10	8.67E-06	2.31E-02	4.51E-02
Waukesha	1.24E-14	1.74E-02	3.80E-04	1.48E-04	1.46E-06	7.32E-11	9.13E-10	8.72E-06	2.32E-02	4.54E-02
Waupaca	1.19E-14	1.66E-02	3.63E-04	1.42E-04	1.40E-06	6.99E-11	8.73E-10	8.33E-06	2.22E-02	4.34E-02
Waushara	1.19E-14	1.66E-02	3.63E-04	1.42E-04	1.40E-06	6.99E-11	8.73E-10	8.33E-06	2.22E-02	4.34E-02
Winnebago	1.22E-14	1.70E-02	3.71E-04	1.45E-04	1.43E-06	7.16E-11	8.93E-10	8.53E-06	2.27E-02	4.44E-02
Wood	1.27E-14	1.77E-02	3.88E-04	1.51E-04	1.49E-06	7.47E-11	9.33E-10	8.91E-06	2.37E-02	4.64E-02
Menominee	1.44E-14	2.00E-02	4.38E-04	1.71E-04	1.69E-06	8.45E-11	1.05E-09	1.01E-05	2.68E-02	5.24E-02

Table E98. County-Level Space Heating Environmental Impacts (effective Space Heating, SC3).

County	Ozone depletion	Global warming	Smog	Acidification	Eutrophication	Carcinogenics	Non carcinogenics	Respiratory effects	Ecotoxicity	Fossil fuel depletion
Unit	kg CFC-11 eq	kg CO2 eq	kg O3 eq	kg SO2 eq	kg N eq	CTUh	CTUh	kg PM2.5 eq	CTUe	MJ surplus
Adams	2.54E-15	3.54E-03	7.75E-05	3.03E-05	2.99E-07	1.49E-11	1.87E-10	1.78E-06	4.74E-03	9.27E-03
Ashland	2.84E-15	3.96E-03	8.67E-05	3.39E-05	3.34E-07	1.67E-11	2.09E-10	1.99E-06	5.30E-03	1.04E-02
Barron	2.71E-15	3.78E-03	8.27E-05	3.23E-05	3.19E-07	1.59E-11	1.99E-10	1.90E-06	5.06E-03	9.89E-03
Bayfield	2.84E-15	3.96E-03	8.67E-05	3.39E-05	3.34E-07	1.67E-11	2.09E-10	1.99E-06	5.30E-03	1.04E-02
Brown	2.44E-15	3.41E-03	7.45E-05	2.91E-05	2.87E-07	1.44E-11	1.79E-10	1.71E-06	4.56E-03	8.91E-03
Buffalo	2.60E-15	3.63E-03	7.94E-05	3.10E-05	3.06E-07	1.53E-11	1.91E-10	1.82E-06	4.85E-03	9.49E-03
Burnett	2.74E-15	3.82E-03	8.37E-05	3.27E-05	3.22E-07	1.61E-11	2.01E-10	1.92E-06	5.11E-03	1.00E-02
Calumet	2.43E-15	3.40E-03	7.43E-05	2.90E-05	2.86E-07	1.43E-11	1.79E-10	1.71E-06	4.54E-03	8.88E-03
Chippewa	2.60E-15	3.63E-03	7.94E-05	3.10E-05	3.06E-07	1.53E-11	1.91E-10	1.82E-06	4.85E-03	9.49E-03
Clark	2.64E-15	3.69E-03	8.07E-05	3.15E-05	3.11E-07	1.56E-11	1.94E-10	1.85E-06	4.93E-03	9.65E-03
Columbia	2.53E-15	3.53E-03	7.72E-05	3.02E-05	2.97E-07	1.49E-11	1.86E-10	1.77E-06	4.72E-03	9.23E-03
Crawford	2.30E-15	3.21E-03	7.01E-05	2.74E-05	2.70E-07	1.35E-11	1.69E-10	1.61E-06	4.29E-03	8.39E-03
Dane	2.35E-15	3.28E-03	7.17E-05	2.80E-05	2.76E-07	1.38E-11	1.72E-10	1.65E-06	4.38E-03	8.57E-03
Dodge	2.41E-15	3.37E-03	7.37E-05	2.88E-05	2.84E-07	1.42E-11	1.77E-10	1.69E-06	4.50E-03	8.81E-03

Door	2.44E-15	3.41E-03	7.45E-05	2.91E-05	2.87E-07	1.44E-11	1.79E-10	1.71E-06	4.56E-03	8.91E-03
Douglas	2.86E-15	3.99E-03	8.72E-05	3.41E-05	3.36E-07	1.68E-11	2.10E-10	2.00E-06	5.33E-03	1.04E-02
Dunn	2.60E-15	3.63E-03	7.94E-05	3.10E-05	3.06E-07	1.53E-11	1.91E-10	1.82E-06	4.85E-03	9.49E-03
Eau Claire	2.60E-15	3.63E-03	7.94E-05	3.10E-05	3.06E-07	1.53E-11	1.91E-10	1.82E-06	4.85E-03	9.49E-03
Florence	2.75E-15	3.83E-03	8.38E-05	3.28E-05	3.23E-07	1.62E-11	2.02E-10	1.93E-06	5.12E-03	1.00E-02
Fond du Lac	2.39E-15	3.33E-03	7.29E-05	2.85E-05	2.81E-07	1.41E-11	1.75E-10	1.68E-06	4.46E-03	8.72E-03
Forest	2.91E-15	4.07E-03	8.89E-05	3.48E-05	3.43E-07	1.71E-11	2.14E-10	2.04E-06	5.44E-03	1.06E-02
Grant	2.30E-15	3.21E-03	7.01E-05	2.74E-05	2.70E-07	1.35E-11	1.69E-10	1.61E-06	4.29E-03	8.39E-03
Green	2.30E-15	3.20E-03	7.01E-05	2.74E-05	2.70E-07	1.35E-11	1.69E-10	1.61E-06	4.28E-03	8.38E-03
Green Lake	2.43E-15	3.40E-03	7.43E-05	2.90E-05	2.86E-07	1.43E-11	1.79E-10	1.71E-06	4.54E-03	8.88E-03
Iowa	2.30E-15	3.21E-03	7.01E-05	2.74E-05	2.70E-07	1.35E-11	1.69E-10	1.61E-06	4.29E-03	8.39E-03
Iron	2.84E-15	3.96E-03	8.67E-05	3.39E-05	3.34E-07	1.67E-11	2.09E-10	1.99E-06	5.30E-03	1.04E-02
Jackson	2.63E-15	3.67E-03	8.04E-05	3.14E-05	3.09E-07	1.55E-11	1.93E-10	1.85E-06	4.91E-03	9.61E-03
Jefferson	2.49E-15	3.47E-03	7.59E-05	2.97E-05	2.92E-07	1.46E-11	1.83E-10	1.74E-06	4.64E-03	9.08E-03
Juneau	2.63E-15	3.67E-03	8.04E-05	3.14E-05	3.09E-07	1.55E-11	1.93E-10	1.85E-06	4.91E-03	9.61E-03
Kenosha	2.22E-15	3.10E-03	6.78E-05	2.65E-05	2.61E-07	1.31E-11	1.63E-10	1.56E-06	4.14E-03	8.11E-03
Kewaunee	2.44E-15	3.41E-03	7.45E-05	2.91E-05	2.87E-07	1.44E-11	1.79E-10	1.71E-06	4.56E-03	8.91E-03
La Crosse	2.29E-15	3.20E-03	7.00E-05	2.74E-05	2.70E-07	1.35E-11	1.68E-10	1.61E-06	4.28E-03	8.37E-03
Lafayette	2.30E-15	3.20E-03	7.01E-05	2.74E-05	2.70E-07	1.35E-11	1.69E-10	1.61E-06	4.28E-03	8.38E-03

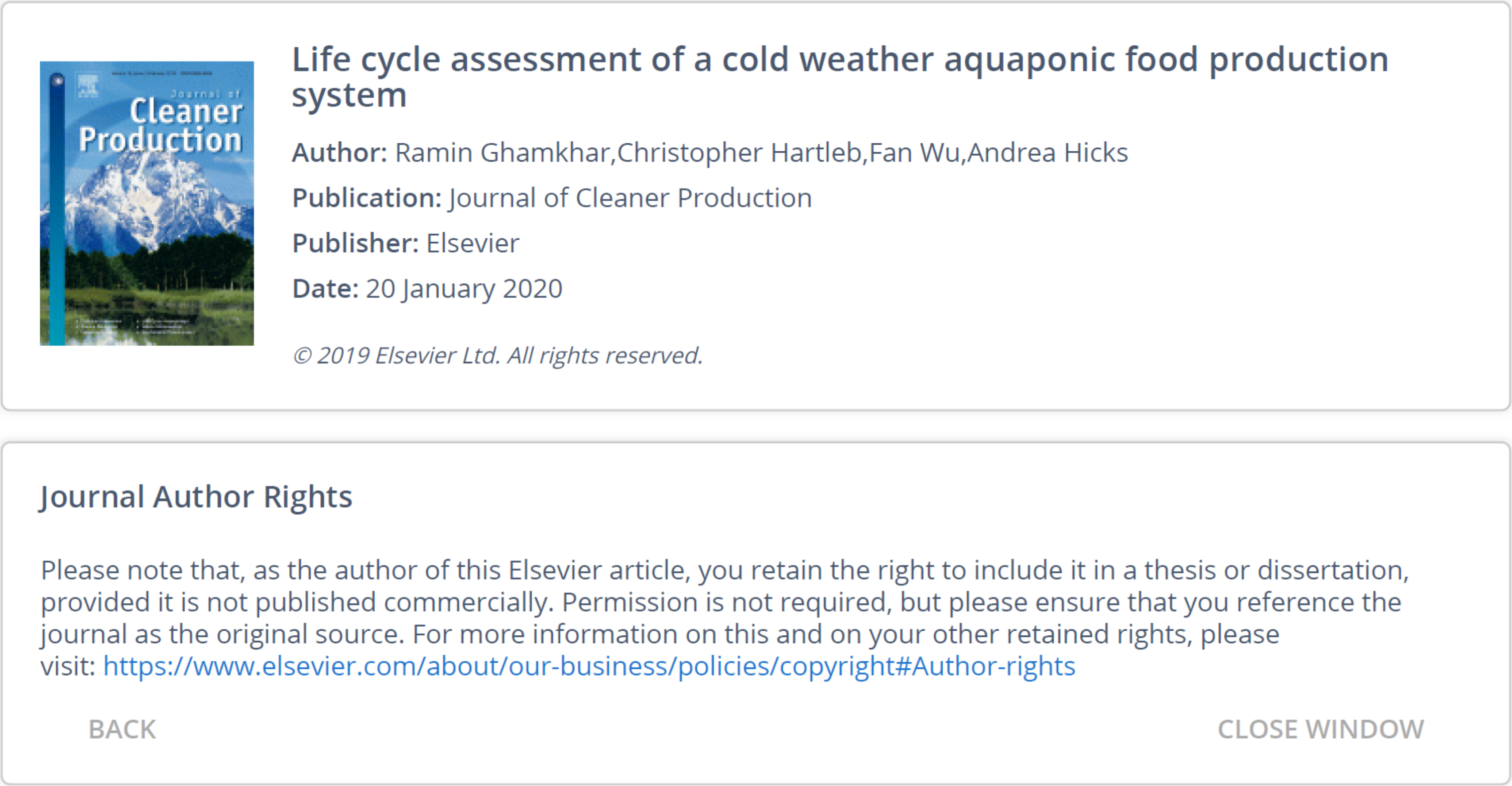
Langlade	2.75E-15	3.83E-03	8.39E-05	3.28E-05	3.23E-07	1.62E-11	2.02E-10	1.93E-06	5.13E-03	1.00E-02
Lincoln	2.75E-15	3.83E-03	8.39E-05	3.28E-05	3.23E-07	1.62E-11	2.02E-10	1.93E-06	5.13E-03	1.00E-02
Manitowoc	2.47E-15	3.45E-03	7.55E-05	2.95E-05	2.91E-07	1.46E-11	1.82E-10	1.73E-06	4.62E-03	9.03E-03
Marathon	2.66E-15	3.71E-03	8.12E-05	3.17E-05	3.13E-07	1.57E-11	1.95E-10	1.87E-06	4.96E-03	9.71E-03
Marinette	2.75E-15	3.83E-03	8.38E-05	3.28E-05	3.23E-07	1.62E-11	2.02E-10	1.93E-06	5.12E-03	1.00E-02
Marquette	2.54E-15	3.54E-03	7.75E-05	3.03E-05	2.99E-07	1.49E-11	1.87E-10	1.78E-06	4.74E-03	9.27E-03
Milwaukee	2.21E-15	3.08E-03	6.74E-05	2.63E-05	2.60E-07	1.30E-11	1.62E-10	1.55E-06	4.12E-03	8.06E-03
Monroe	2.30E-15	3.20E-03	7.01E-05	2.74E-05	2.70E-07	1.35E-11	1.69E-10	1.61E-06	4.28E-03	8.38E-03
Oconto	2.44E-15	3.41E-03	7.45E-05	2.91E-05	2.87E-07	1.44E-11	1.79E-10	1.71E-06	4.56E-03	8.91E-03
Oneida	2.75E-15	3.83E-03	8.39E-05	3.28E-05	3.23E-07	1.62E-11	2.02E-10	1.93E-06	5.13E-03	1.00E-02
Outagamie	2.50E-15	3.50E-03	7.65E-05	2.99E-05	2.95E-07	1.47E-11	1.84E-10	1.76E-06	4.67E-03	9.15E-03
Ozaukee	2.47E-15	3.45E-03	7.55E-05	2.95E-05	2.91E-07	1.46E-11	1.82E-10	1.73E-06	4.62E-03	9.03E-03
Pepin	2.50E-15	3.49E-03	7.63E-05	2.98E-05	2.94E-07	1.47E-11	1.84E-10	1.75E-06	4.66E-03	9.12E-03
Pierce	2.50E-15	3.49E-03	7.63E-05	2.98E-05	2.94E-07	1.47E-11	1.84E-10	1.75E-06	4.66E-03	9.12E-03
Polk	2.64E-15	3.68E-03	8.06E-05	3.15E-05	3.10E-07	1.55E-11	1.94E-10	1.85E-06	4.93E-03	9.64E-03
Portage	2.75E-15	3.84E-03	8.41E-05	3.28E-05	3.24E-07	1.62E-11	2.02E-10	1.93E-06	5.14E-03	1.01E-02
Price	2.88E-15	4.03E-03	8.81E-05	3.44E-05	3.39E-07	1.70E-11	2.12E-10	2.02E-06	5.38E-03	1.05E-02
Racine	2.26E-15	3.16E-03	6.91E-05	2.70E-05	2.66E-07	1.33E-11	1.66E-10	1.59E-06	4.22E-03	8.27E-03
Richland	2.30E-15	3.21E-03	7.01E-05	2.74E-05	2.70E-07	1.35E-11	1.69E-10	1.61E-06	4.29E-03	8.39E-03

Rock	2.21E-15	3.08E-03	6.74E-05	2.63E-05	2.60E-07	1.30E-11	1.62E-10	1.55E-06	4.12E-03	8.06E-03
Rusk	2.71E-15	3.78E-03	8.27E-05	3.23E-05	3.19E-07	1.59E-11	1.99E-10	1.90E-06	5.06E-03	9.89E-03
Saint Croix	2.67E-15	3.73E-03	8.16E-05	3.19E-05	3.14E-07	1.57E-11	1.96E-10	1.87E-06	4.99E-03	9.76E-03
Sauk	2.30E-15	3.21E-03	7.01E-05	2.74E-05	2.70E-07	1.35E-11	1.69E-10	1.61E-06	4.29E-03	8.39E-03
Sawyer	2.81E-15	3.92E-03	8.57E-05	3.35E-05	3.30E-07	1.65E-11	2.06E-10	1.97E-06	5.24E-03	1.02E-02
Shawano	2.44E-15	3.41E-03	7.45E-05	2.91E-05	2.87E-07	1.44E-11	1.79E-10	1.71E-06	4.56E-03	8.91E-03
Sheboygan	2.47E-15	3.45E-03	7.55E-05	2.95E-05	2.91E-07	1.46E-11	1.82E-10	1.73E-06	4.62E-03	9.03E-03
Taylor	2.87E-15	4.00E-03	8.76E-05	3.42E-05	3.37E-07	1.69E-11	2.11E-10	2.01E-06	5.35E-03	1.05E-02
Trempealeau	2.29E-15	3.20E-03	7.00E-05	2.74E-05	2.70E-07	1.35E-11	1.68E-10	1.61E-06	4.28E-03	8.37E-03
Vernon	2.63E-15	3.67E-03	8.04E-05	3.14E-05	3.09E-07	1.55E-11	1.93E-10	1.85E-06	4.91E-03	9.61E-03
Vilas	2.75E-15	3.84E-03	8.39E-05	3.28E-05	3.23E-07	1.62E-11	2.02E-10	1.93E-06	5.13E-03	1.00E-02
Walworth	2.21E-15	3.08E-03	6.74E-05	2.63E-05	2.60E-07	1.30E-11	1.62E-10	1.55E-06	4.12E-03	8.06E-03
Washburn	2.81E-15	3.92E-03	8.57E-05	3.35E-05	3.30E-07	1.65E-11	2.06E-10	1.97E-06	5.24E-03	1.02E-02
Washington	2.47E-15	3.45E-03	7.54E-05	2.95E-05	2.91E-07	1.45E-11	1.81E-10	1.73E-06	4.61E-03	9.02E-03
Waukesha	2.49E-15	3.47E-03	7.59E-05	2.97E-05	2.92E-07	1.46E-11	1.83E-10	1.74E-06	4.64E-03	9.08E-03
Waupaca	2.38E-15	3.32E-03	7.26E-05	2.84E-05	2.79E-07	1.40E-11	1.75E-10	1.67E-06	4.43E-03	8.68E-03
Waushara	2.38E-15	3.32E-03	7.26E-05	2.84E-05	2.79E-07	1.40E-11	1.75E-10	1.67E-06	4.43E-03	8.68E-03
Winnebago	2.43E-15	3.40E-03	7.43E-05	2.90E-05	2.86E-07	1.43E-11	1.79E-10	1.71E-06	4.54E-03	8.88E-03
Wood	2.54E-15	3.54E-03	7.75E-05	3.03E-05	2.99E-07	1.49E-11	1.87E-10	1.78E-06	4.74E-03	9.27E-03

Menominee	2.87E-15	4.01E-03	8.77E-05	3.43E-05	3.38E-07	1.69E-11	2.11E-10	2.01E-06	5.36E-03	1.05E-02

Appendix F

Journal Permissions



Life cycle assessment of a cold weather aquaponic food production system

Author: Ramin Ghamkhar,Christopher Hartleb,Fan Wu,Andrea Hicks

Publication: Journal of Cleaner Production

Publisher: Elsevier

Date: 20 January 2020

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Comparative environmental impact assessment of aquafeed production: Sustainability implications of forage fish meal and oil free diets

Author: Ramin Ghamkhar,Andrea Hicks

Publication: Resources, Conservation and Recycling

Publisher: Elsevier

Date: October 2020

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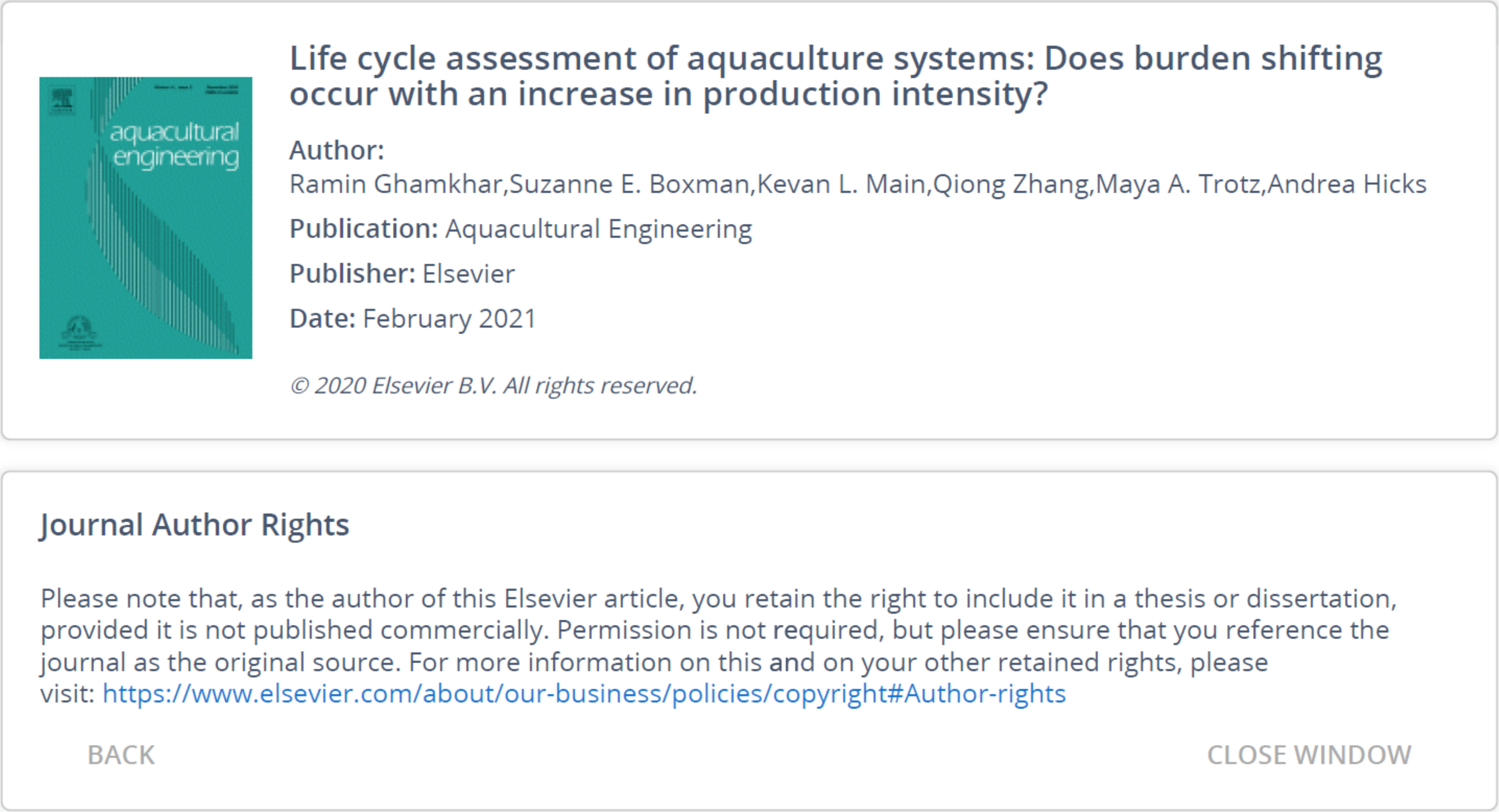

Life cycle assessment of aquaculture systems: Does burden shifting occur with an increase in production intensity?

Author:
Ramin Ghamkhar,Suzanne E. Boxman,Kevan L. Main,Qiong Zhang,Maya A. Trotz,Andrea Hicks

Publication: Aquacultural Engineering

Publisher: Elsevier

Date: February 2021

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Appendix G

Curriculum Vitae (CV)

Ramin Ghamkhar, MS

PhD Candidate

1415 Engineering Dr, 2231 Engineering Hall, Madison, WI 53706

Tel: 1-716-440-9363; E-mail: ghamkhar@wisc.edu;

Linkedin: https://www.linkedin.com/in/ramin-ghamkhar; Twitter: @RaminGhamkhar

EDUCATION

University of Wisconsin-Madison

PhD. in Civil and Environmental Engineering, expected: May 2021

GPA: 3.93/4.00

Dissertation: “Food-Energy-Water Nexus”, “Sustainability in Aquaponics and Aquaculture Food Production Systems”

Advisor: Dr. Andrea Hicks

- Life Cycle Assessment (LCA)
- Integrated Economic and Environmental Evaluation of Processes
- Analysis and Optimization of Aquaponic Systems
- Green Chemistry
- Creating, Developing, and Utilizing GIS maps

Minor in Sustainability

State University of New York at Buffalo

M.S. in Civil Engineering with a concentration in Environmental Engineering, June 2018

GPA: 3.64/4.00

Thesis: “Catalytic Oxidation of Nitric Oxide using Hyper-Cross-linked Porous Polymers: Impact of Physiochemical Properties on Conversion Efficiency”

Advisor: Dr. John D. Atkinson

- Air pollution control technologies
- Synthesized microporous polymer from the self-cross-linking of 4,4′-Bis(chloromethyl)-1,1′-biphenyl
- Characterized physical and chemical properties of polymers
- Functionalized polymer with amine or benzene for NO adsorption and oxidation
- Tailored pore size distribution of self-crosslinked 4,4′-Bis(chloromethyl)-1,1′-biphenyl by modifying the synthesis conditions
- Assessed catalytic oxidation of nitric oxide (NO) using microporous polymers

Sharif University of Technology

B.S. in Chemical Engineering, June 2016

GPA: 16.07/20.00

Project: “Designing an Experimental Wastewater Treatment Plant Utilizing Advanced Oxidation Process for Phosphorus and Nitrogen Removal”

Advisor: Dr. Mehdi Borghei

- Wastewater biological and chemical treatment: BOD and phosphorus removal utilizing integrated fixed-bed activated sludge (IFAS) reactors

PUBLICATIONS

Published:

- **Ghamkhar, R.**, Hartleb, C., Wu, F., Hicks, A. (2019) “Life Cycle Assessment of a Cold Weather Aquaponic Food Production System”. Published in *JCLP 244, 118767.*
- Wu, F., **Ghamkhar, R.**, Ashton, W., Hicks, R. (2019) “Sustainable seafood and vegetable production–aquaponics as a potential opportunity in urban areas”. Published in *IEAM 15 (6), 832-843.*
- **Ghamkhar, R.** (2018) “Catalytic Oxidation of Nitric Oxide Using Hyper-Cross-Linked Porous Polymers: Impact of Physiochemical Properties on Conversion Efficiency”. MS Thesis.
- Ghafari, M., **Ghamkhar, R.**, Atkinson, J.D. (2018) “NO Oxidation in Dry and Humid Conditions Using Hyper-Cross-Linked Polymers: Impact of Surface Chemistry on Catalytic Conversion Efficiency”. Published in *Fuel 241, 564-570.*
- **Ghamkhar, R.**, Hicks, A. (2020) “Comparative Environmental Impact Assessment of Aquafeed Production: Sustainability implications of fish oil and meal free diets”. Published in *RCR 161, 104849.*
- Wu, F., Zhou, Z., Sekeryan S., **Ghamkhar, R.**, Hicks, A. (2020) “Assessing the environmental impact and payback of carbon nanotube supported CO2 capture technologies using LCA methodology”. Published in *JCLP 270, 122465.*
- Hicks, A., Sekeryan S., Kontar, W., **Ghamkhar, R.**, Rodriguez M. (2020) “Personal respiratory protection and resiliency in a pandemic, the evolving disposable versus reusable debate and its effect on material usage”. Published in *RCR.*
- **Ghamkhar, R.**, Boxman, S., Main, K., Zhang, Q., Trotz, M., Hicks, A., (2020) “Life Cycle Assessment of Aquaculture Systems: Does Burden Shifting Occur with an Increase in Production Intensity?”. Published in *Aquacultural Engineering.*

Under Journal Review:

- **Ghamkhar, R.**, Rabas, Z., Hartleb, C., Hicks, A. (2020) “Integrated Economic and Environmental Assessment of an Aquaponic System”. To be published in *JIE*.
- **Ghamkhar, R.**, Hicks, A., (2020) “Multi-Criteria Decision Analysis and Life Cycle Assessment Model for Optimal Product Selection: Case Study of Aquafeeds”. To be published in *AS&T.*

Under Preparation:

- **Ghamkhar, R.**, Stanker, C., Hicks, A. (2020) “Environmental Implications of Local Aquaculture Food Production: A Potential Food Mileage Reduction Strategy for Remote Regions”. To be published in *Nature Food.*

RESEARCH SKILLS & EXPERIENCE

- **Proposal Writing**
  - Assistance in Proposal Writing (Link), National Science Foundation (NSF) Research Award # 1942110, Environmental Impacts of Closed Loop Food Production: Aquaponics as a Case Study, Jan 2020.
- **Computational Skills**:
  - Life Cycle Assessment (SimaPro 8.1, OpenLCA)
  - Geographic Information Systems (ArcGIS 10.5)
  - Multi-Criteria Decision Analysis (VisualPROMETHEE)
  - Agent-Based Modeling (NetLogo 6.0)
  - Other: Programming (MATLAB), Statistic Analysis (SataSE), Design (SolidWorks), Chemical Equilibrium Modeling (Visual MINTEQ), Hydraulics Modeling (HEC-RAS, EPANET), Visualization (Visio)
- **Materials Characterization Techniques**:
  - Fourier-Transform Infrared (FT-IR) Spectroscopy
  - BET Surface Area and Porosity Analyzer
  - Scanning Electron Microscopy (SEM) Spectroscopy
  - Bulk Elemental Analysis (CHN)
- **Experimental Skills**:
  - Friedel-Crafts Reaction
  - Surface Functionalization
  - Other: Porosity Control, VOC Adsorption, Material Science
- **Community-Based Projects:**
  - Evaluation of the Environmental, Economic and Social Impacts of Compliance Alternatives - The Village of Monticello Wastewater Treatment Facility, 2018.
  - Developing a Pollinator Habitat Assessment Tool - Dane County’s Pollinator Protection Plan, 2019.

TEACHING EXPERIENCE

- **Teaching Assistant:**
  - Civil and Environmental Engineering Decision Making, CEE494, UW-Madison, 2020.
  - Hydraulics and Hydrology, CIE 343, University at Buffalo, 2018.
  - Introduction to Environmental Engineering, CIE 340, University at Buffalo, 2017.
  - Geology for Engineers, GLY 103, University at Buffalo, 2017.
  - Principles of Chemistry Olympiad, ATCCE high school, 2013.

AWARDS, HONORS AND GRANTS

- Planetary Health Scholarship, Spring 2020, University of Wisconsin - Madison Global Health Institute, Dec 2019.
  - Media Mentions: UW-Madison; Global Health Institute (Link), Department of Civil and Environmental Engineering (Link), College of Engineering (Link).
- Master Thesis Award, 1st Place, Air and Waste Management Association, Apr 2019.
- Semifinalist for the 2020-21 UW–Madison Three Minute Thesis Competition, 3MT®, October 2020 (ongoing competition).
- Granted Scholarship as Research Assistantship, Civil and Environmental Engineering Department at UW- Madison, Aug 2018.
- Granted Scholarship as Teaching Assistantship, Civil, Structural and Environmental Engineering Department at SUNY at Buffalo, Jan 2017, Aug 2017, and Jan 2018.
- Semi-finalist in Chemistry National Science Olympiad in Iran, May 2010.
- Ranked among the top 0.3% of more than 350,000 participants in Iranian University Entrance Exam, July 2012.

PROFESSIONAL MEMBERSHIPS

- Air & Waste Management Association (A&WMA, International and Local Niagara Frontier Section), 2017 – 2018.
- Society of Environmental Toxicology and Chemistry (SETAC, North America and Midwest), 2018 – Present.
- International Society for Industrial Ecology (IS4IE), 2020 – Present.

SELECTED CONFERENCES / CONTRIBUTED PRESENTATIONS

- International Society for Industrial Ecology (IS4IE) Biennial Conference, Tsinghua University, Beijing, China, July 07-11, 2019.
- Society of Environmental Toxicology and Chemistry (SETAC) North America 40th Annual Meeting, Toronto, Canada, November 03-07, 2019.
- International Association of Great Lakes Research (IAGLR) Annual Conference, Brockport, New York, US, June 10-14, 2019.
    - Life Cycle Assessment of an Aquaponics Food Production System, Identification and Minimization of Impact Hotspots.
- American Center for Life Cycle Assessment (ACLCA) Conference, Virtual, September 22-24, 2020.
    - Life Cycle Assessment and Economic Analysis of an Aquaponic System.
- Society of Environmental Toxicology and Chemistry (SETAC) North America 41th Annual Meeting, Virtual, November 15-19, 2020.
    - Comparative Environmental Impact Assessment of Aquafeed Production: Sustainability implications of forage fish meal and oil free diets.
    - Live Discussion Session: Enhancing the Usability and Value of LCA Results, Panelist.

PROFESSIONAL SERVICE & LEADERSHIP EXPERIENCE

- Peer Reviewed Journal Reviewer
    - Journal of Cleaner Production, 2019 Impact Factor: 7.246 (Reviewed 2 manuscripts).
- Summer Undergraduate Research Experience (SURE) Mentoring:
    - Environmental Paybacks of Electricity Generation Using Solar PV Panels, Data Acquisition, Poster Preparation, and GIS Mapping Techniques, University of Wisconsin-Madison, 2019.
    - Activated Carbons Adsorption and Desorption Properties, Material Characterization Experiments, University at Buffalo, 2018.
- Conference board member, the 5th Health, Safety and the Environment (HSE) conference, Sharif University of Technology, March 2014.
- Conference board head, the 6th Health, Safety, and the Environment (HSE) conference, Sharif University of Technology. March 2016.

- Organizer at "Environmental Impact Assessment/ Fundamentals and Applications” workshop, Center for Process Design, Safety and Loss Prevention (CPSL), Sharif University of Technology, February 2016.