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Executive summary

The Eco-Intensification Sustainability Index was a collaborative effort between University of Stirling and University of Venice, with large contributions from Zachodniopomorski Uniwersytet Technologiczny, Thunen Institute, GIFAS, AFBI and others. The aims of the EISI were to provide a sustainability index that covered the whole value chain of different aquaculture production but went beyond the narrow and uncontextualized scope of Life Cycle Assessment (LCA). LCA in conjunction with Value Chain Analysis and targeted aquaculture specific indicators was foreseen as a better method to assess the overall sustainability of aquaculture value chains in Europe, including environmental, socio-economic and animal welfare indicators that provided a "One Health" perspective on sustainability.

At the start of the process, UoS, UNIVE and TI engaged to assess the relevance of different indicators to European aquaculture, through iterative sessions and workshops a list of indicators based around LCA and VCA principles was developed. Key aspects were around applicability and ease of data collection, endeavouring to ensure that data would be readily available, at least for aquaculture enterprises under study. Indicators that would require extra data collection by enterprises themselves were rejected. Field work was planned for three months in each of Norway, Poland and Spain to collect data from the Atlantic salmon, common carp, and seabass/ seabream industries respectively. However, due to COVID restrictions data collection was only completed for Norwegian salmon with partial data collected in Poland and no data in Spain. Further data was collected from UK shellfish industries although not enough to complete a full EISI evaluation. The data in this report covers the full EISI for Norwegian salmon together with partial indicator data for Poland and UK shellfish. In addition there is a performance assessment of the novel feed ingredients trials carried out in WP1 using a selection of the most important environmental indicators.

The Norwegian salmon EISI included data from three major feed producers, nine farms, three hatcheries and two processors. Data showed similar environmental impacts to other studies with Global Warming potential at just over 2500kgCO_2eq per tonne at farm gate. FIFO was 9.57 making it a net producer of fish. Gender balance in the industry was close to even although production was dominated by males with more females in processing which meant overall, more enterprises were dominated by males. Almost all of the production went to either human or animal nutrition with little waste. The EISI was presented as a traffic light system that showed a range of performance within the four sustainability categories (environment, social responsibility, economic performance and animal welfare). The economic performance showed overall good performance with no poor performers at all, but the other three categories showed that while most of the industry performed very well there were some areas for improvement, including gender ratios, mortality, welfare checks and benthic impact in some farms.

Carp data was only collected from a single feed producer and three farms. The farms were very different from one another, including an extensive system with no feed inputs, a semi intensive system that relied on unprocessed triticale for feed and a semi intensive system that used only formulated feed. All farms had major losses from predation, with over 90% mortality in some cases leading to far less productivity per FTE compared to salmon. All labour was male. However, the feed had a much low carbon footprint made up with minimally processed agricultural ingredients and a small marine ingredient inclusion. Consequently, the industry average FIFO was calculated at only 0.027, making it overwhelmingly a net producer of fish. However, other data suggest that there are several sustainability challenges apart from high mortality and low productivity with limited markets, few

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product forms and some welfare concerns which should be improved for the long term sustainability of the industry, which is largely supported within D4.2.

Primary data on shellfish had only been collected from processors at the time of the completion of this report. Farm data was taken from literature which showed generally low environmental impact. However, some sustainability concerns had been flagged from the limited primary data that could be collected on large amounts of losses between the mussel farm production and processing, amounting to around 20% by mass which had no market and were being sent to landfill. These losses represent a significant opportunity for the circular economy to valorise within the feed industry.

Novel feed assessments were made based on data from feed trials led by Sparos on the five major finfish species. LCA from literature sources showed that novel feed ingredients had particularly high energy and sometimes substrate demands for their production and processing, resulting in high LCA impacts across the majority of indicators. Some modest improvements in FCR did not make-up for very large increases in LCA impacts in most cases. PAPs and seafood by-product ingredients proved to be much better across all indicators used, including FIFO (which novel ingredients also scored well). The conclusions from the analysis were that, although investment in novel feed ingredient improvements should be made, a lot more investment should be made in improving the acceptability of PAPs and by-products which although have high nutritional performance, low environmental impacts and low costs, are not well adopted because of poor perceptions among consumers and particularly, retail stakeholders.

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Glossary

AP	Acidification Potential
ASC	Aquaculture Stewardship Council
BP	By-Product
BRU	Biotic Resource Use
CEAP	Circular Economy Action Plan
CFC	Chloro-Fluoro-Carbon
CWU	Consumptive Water Use
EC	European Commission
EISI	Eco-intensification Sustainability Index
EP	Eutrophication Potential
FAO	Food and Agriculture Organisation of the United Nations
FCR	Feed Conversion Ratio
FF	Forage Fish
(e)FIFO	(Economic) Fish In Fish Out ratio
FU	Functional Unit
GAA	Global Aquaculture Alliance
GHG	Greenhouse Gas
GLO	Global
GlobalGAP	Global Good Aquaculture Practice
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LU	Land Use
LUC	Land Use Change
NO	Norway
NPP	Net Primary Productivity
NUSAP	Numerical Unit Spread Assessment Pedigree
ODP	Ozone Depletion Potential
PCO	Photochemical Oxidation potential
PEFCR	Product Environmental Category Rules
RoW	Rest of the world
WSI	Water Stress Index
WTA	Withdrawal To Availability ratio

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Section 1. Introduction to the EISI and Life Cycle Assessment

1.1 Introduction

This document describes the concepts and methodology underpinning the data collection for the Eco-Intensification Sustainability Index (EISI) that is the principle measure of the environmental performance of GAIN innovations throughout the project. The EISI is principally made up of Life Cycle Assessment (LCA) based indicators, supported by aquaculture specific environmental and socio-economic indicators to give a broad basis for sustainability gains. The initial work provides an evidence based benchmark for EU/EEA aquaculture industries in Norway (salmon), Poland (carp), Spain (Seabass/ seabream), Italy (trout) and the UK (mussels and oysters) against which innovations can be measured.

The methodology described is built on experiences from the FP7 funded SEAT and H2020 funded EURASTiP projects and dovetails with activities in WP3 and WP4 on Value Chain Analysis (VCA) which are not extensively described in this document. This introduction sets out the background to the EISI, its context in WP4 and connection to other activities in the project. Section 1 outlines the methodological steps and gives a brief overview of considerations of different indicators that are relevant to EU aquaculture and their inclusion in the EISI. Section 2 gives a brief overview of the systems and value chains under study with particular reference to the specific challenges to data collection for the EISI. Section 3 describes the data that is required to construct the EISI, including primary, secondary and background data. Section 4 describes the initial stakeholder/ expert consultation period which was undertaken to draw up the indicator list and survey questions for the data collection. Section 5 discusses the research questions that are relevant to the innovations within GAIN. Section 6 describes the LCA modelling procedure, including functional unit, cut-off criteria, system boundaries, allocation etc. Section 7 describes the data analysis that is proposed to construct the EISI from the raw data; e.g. weighting, aggregation, normalisation, scoring etc. The original surveys that were used for each part of the value chain are included in the appendices. Section 8 compares the performance of novel feed ingredients with a focus on environmental indicators from the EISI. Section 9 provides an EISI benchmark for Norwegian salmon providing a comprehensive assessment of the industry against which innovation can be tested. Section 10 identifies key findings from the EISI work and makes recommendations for policy and further development and application of the EISI.

1.2 Relationship to other tasks in WP4 and others

The objectives of WP4 are to combine outcomes from WP1 (Production and Environment), WP2 (Enhancement of secondary outputs), and WP3 (Policy and Markets) to increase quantity, quality, sustainability, and traceability, and to apply appropriate metrics to estimate performance in both economic and ecological terms. The outcomes of these performance assessments will relate to citizens, policy-makers, and markets, with the overarching aim of combining the RTD work in GAIN into a blueprint for effective eco-intensification of European aquaculture. WP4 examines the potential of eco-intensification options explored in GAIN by (i) applying well-tested socio-economic techniques, including farm-scale and value-chain analyses; (ii) building and applying a multi-metric index to assess sustainability, using indicators of performance for production, environment and social categories

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(EISI); (iii) developing applications for increasing connectivity of producers and consumers, and increasing citizen participation; and (iv) analysing the volume and niche aspects of aquaculture production, with an emphasis on the key role that sustainability, well-being, animal welfare, local sourcing, and traceability play in determining consumer choice and market success.

Specifically WP4 will identify and analyse

- the configurations of the selected aquaculture value chains;
- the dynamics, opportunities and threats in the selected value chains;
- the profitability and technical efficiency of the production of the selected species;
- the distribution of benefits along the selected value chains, their environmental and social impact, and the assessment of their equity for different groups

The EISI was conceptualised by researchers at UoS following work on the EU FP7 funded “Sustaining Ethical Aquaculture Trade” project (SEAT), which developed a sustainability index for Asian seafood products traded to the EU. The indicators and methods were developed by the UoS in collaboration with UNIVE. UoS is conducting the majority of the benchmarking exercises of EU aquaculture systems, while UNIVE is conducting most of the modelling associated with GAIN innovations.

1.3 Research questions

Research questions for VCA and LCA have been identified around three topics which are covered in Deliverables 4.2, 4.3 and 4.4

I. Value chain configuration
   - What is the overall configuration of selected value chains for key European aquaculture products?
   - Who are the local and international stakeholders (governments, donors, certifiers, NGOs etc.) who engage with the value chain?

II. Innovation
   - How does the institutional framework in which producers operate affect the value chain actors?
   - Which innovations are likely to succeed in bringing about managerial, logistical and governance changes that will result in more benefits to producers and consumers of farmed aquatic products?
   - Which innovations are likely to result in long-term sustainability benefits to the EU aquaculture industry

III. Sustainability
   - How do different systems, scales and managerial approaches affect the sustainability of EU aquaculture operations?
   - What factors are most important for the sustainability of different EU aquaculture operations in the face of future scenarios of change, such as globalization, competition, rise in food prices, climate change etc?

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- What are the comparative advantages (opportunity costs and benefits) of producers in different aquaculture industries?
- How do different EU aquaculture industries support local livelihoods and communities?

1.4 Rationale

The research questions find their basis in integrating identification of structural, managerial and technical innovation within aquaculture through VCA with sustainability assessments grounded in LCA. Value chain approaches aim to assess the inter-linkage of different actors involved in the production, processing and distribution of a product and the institutional framework affecting it. VCA can also identify where value is created or lost and where the critical points for improvement lay. Therefore, it integrates with economic and social sustainability assessments and complements the EISI. It can also be valuable to allow for a move away from assessing socio economic impacts of value chains exclusively at the producer level and to include those involved in supply chains, distribution, processing and trading.

1.5 Methodological framework

The EISI is underpinned by Life Cycle Assessment, which usually follows ISO guidelines (ISO 2006a, 2006b). LCA is becoming more common as an environmental impact evaluation tool because it gives a holistic assessment across several different categories of impacts that are accumulated throughout the life-span of a product. Therefore, it avoids problem shifting between different stages of production and between different types of impacts. LCA typically involves a large data set, sourced from producers, literature and LCA databases which needs careful planning. The steps set out by ISO (2006a; 2006b) are designed to aid practitioners plan data collection and modelling and are described below (Figure 1). The LCA framework prescribes the development and data collection for the EISI.

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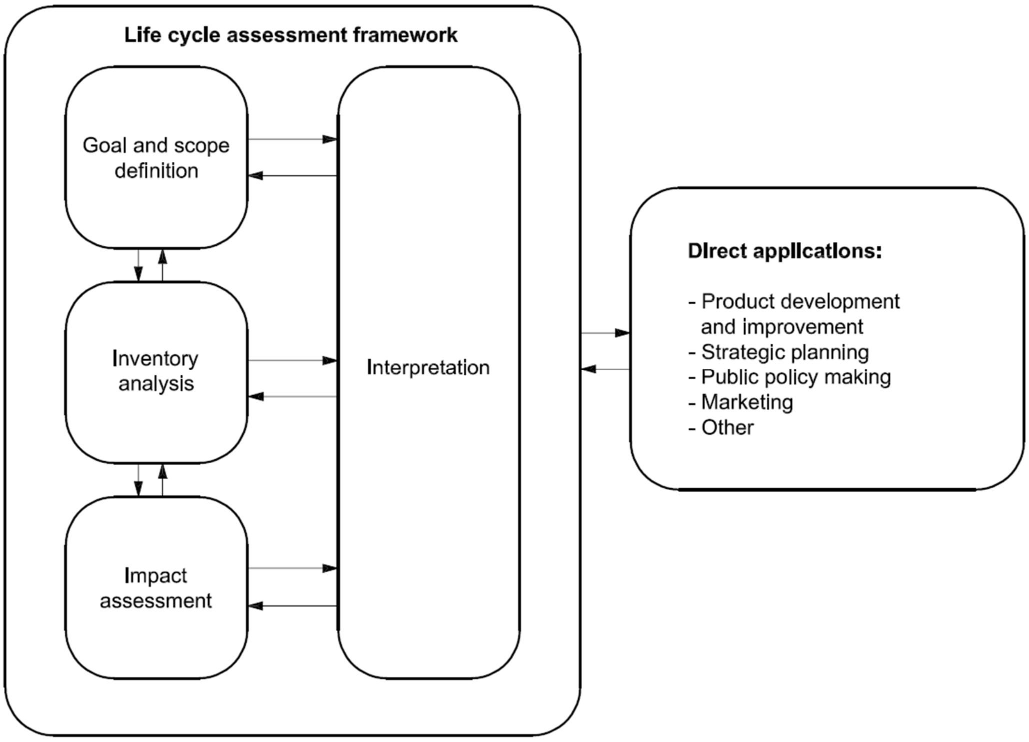

Figure 1.1 Overview of Life Cycle Assessment steps according to ISO 14040 (ISO 2006a)

1) Goal and Scope

The Goal and Scope phase sets out the basic parameters of the study and is usually dictated by the audience and main objectives, as a commercial product development, planning or marketing exercise, or an academic, independent assessment aimed at policy makers or others. This determines how the results will be used and presented, and their application.

Critical points to be defined during the Goal and Scope are the boundaries of the system, i.e. what parts of the value chain are to be included in the data collection, the reference unit (known as the "Functional Unit") for the study, the cut-off criteria (what processes will be included or not, usually based on their relative contribution to overall impact), the partitioning procedure between multi-functional processes (how much impact should be attributed to different co-products), the impact categories that will be included and the analytical method. Assessments may be either "end-point" or "mid-point" and "consequential" or attributional". Typically, end-point assessments try to evaluate tangible changes such as how much the planet will warm due to greenhouse gas (GHG) emissions, whereas a mid-point assessment only quantifies the emissions and the "potential" to cause impact. Consequential assessments measure the consequence of different actions, such as, quantifying GHG emissions saved by adopting a certain process/ system, whereas attributional assessments measure the absolute generation of emissions.

Other considerations cover issues such as temporal, geographical and technology scope, the mode of analysis employed and the overall level of sophistication of the study. This document will cover all of

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the main aspects of the Goal and Scope in subsequent Sections along with other considerations of the EISI which normally fall outwith the remit of a typical LCA study.

2) Inventory Analysis

Inventory analysis involves the compiling of all relevant input and output data of the production systems within the value chain under study, within the boundaries defined at the Goal and Scope phase. It is generally the most time-consuming part of the LCA as it involves complex survey work with multiple stakeholder actors, many of which may not have been previously identified. It is an iterative process that often requires trust and confidence building between the data collectors and providers, especially as the data are often commercially sensitive.

Often the first step is to characterise the systems and flows of materials and value by constructing flow diagrams. Information can be gathered from any previous studies of similar systems and by stakeholder interaction. The flow diagrams provide an initial basis for understanding the most important parts of the value chain and their interconnectivity to inform primary data collection and where the cut-off points might be. The initial starting point is usually the use of the product in question with upstream (resource use) and downstream processes (waste management and circular economy options) characterised around it. The data can be used to determine how many of each stakeholder must be contacted to provide a representative level of data that meet the goal and scope objectives.

The data that is collected for an LCA is called a Life Cycle Inventory and may be separated into three parts: 1; primary data that is collected directly from stakeholders via survey or other means, 2; secondary data that is collected by literature searches and 3; background data that is contained within LCA databases such as EcoInvent (https://ecoinvent.org/). Typically, primary data are those relating directly to the system under study, such as the farm, feed manufacturers, and processors in the case of aquaculture. In addition, input/output data of materials manufactured in the pilot level innovations and their performance in farm trials included within GAIN are also considered primary level data. Secondary data includes the growing and manufacture of feed ingredients as they are often produced in other continents and it is not feasible to collect primary data for these processes within the same project. Background data typically include emissions data from engines and energy provision though national energy mixes. Data collection is usually an iterative process which goes through an initial cleaning and quality evaluation process before contacting participants for clarification of data or further data collection. Data must be further assessed for quality and representativeness throughout the data collection period. During the data evaluation steps the data categories are identified and quantified into the reference flows of materials, energy and value between the process nodes within the value chain according to the initial flow diagrams. The data includes economic flows, which are generally goods or services that have an economic value, produced in manufacturing processes, or environmental flows which are either raw material resources or emissions taken from or emitted to the biosphere (e.g. Figure 2).

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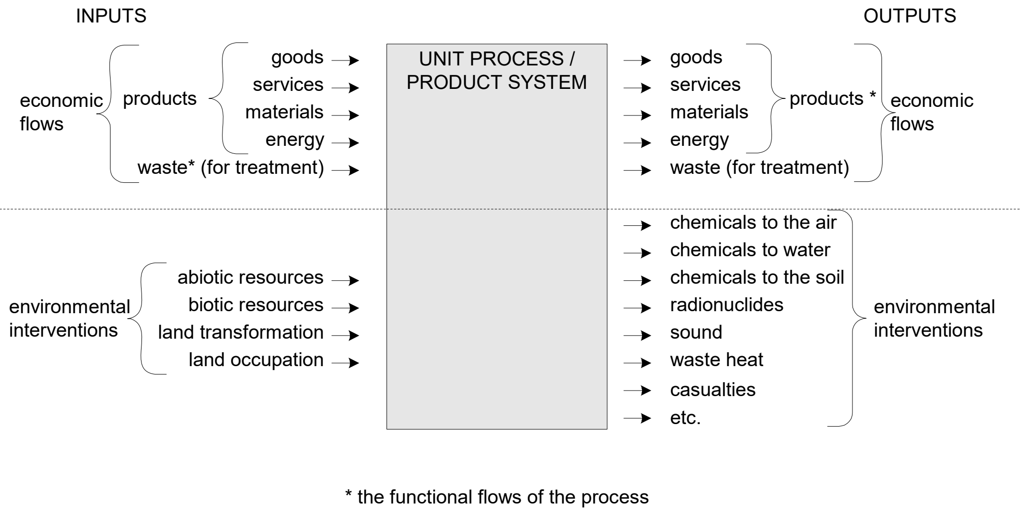

Figure 1.2. Examples of life cycle data categories (Guinée et al., 2002)

Data must be assessed for cut-off purposes. It is rarely possible to collect data on all processes in the life cycle of a product and it saves a lot of time to determine those processes which have little effect on the overall impact assessment early on, after the initial data scoping. In most cases the cut-off criteria will be according to impact contribution (e.g. processes that contribute to less than 1% of emissions are excluded), but processes may also be assumed if there is little access to data or likelihood of obtaining it. In such cases assumptions must be made according to similar processes in similar systems.

The end of the LCI phase of an LCA is marked by compilation of a series of inventory tables for each process within the system boundary, defined by clearly defined reference flows.

3) Impact Assessment

The Impact Assessment phase is the main modelling phase where LCI emissions are compiled and characterised into impact categories. The method of impact assessment dictates exactly how this is performed and although there are broad similarities, there are differences concerning the inclusion of different categories, end-point vs mid-point assessments and attributional vs consequential assessments outlined above. The assessment method will be decided during the Goal and Scope phase.

The first decision to be made following choice of assessment method is which impact categories to include. Although this is largely dictated by the choice of impact assessment method and built into LCA software (baseline categories), the practitioner can choose to omit some categories or include others (study specific). These may need to be defined by the user. Some typical mid-point impact categories are shown in Table 1. The methodological choices concerning which impact categories have been included in the LCA part of the EISI are provided in Section 6.

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Table 1.1. Impact categories for seafood production (Pelletier et al 2007)

Impact Category	Description of Impacts
Global Warming	Contributes to atmospheric absorption of infrared radiation
Acidification	Contributes to acid deposition
Eutrophication	Provision of nutrients contributes to biological oxygen demand
Photochemical Oxidant Formation	Contributes to photochemical smog
Aquatic/Terrestrial Ecotoxicity	Contributes to conditions toxic to flora and fauna
Human Toxicty	Contributes to conditions toxic to humans
Energy Use	Contributes to depletion of non-renewable energy resources
Abiotic Resource Use	Contributes to depletion of non-renewable resources
Biotic Resource Use	Contributes to depletion of renewable resources
Ozone Depletion	Contributes to depletion of stratospheric ozone

Assessments are made using specialist LCA software such as Simapro or GABI which convert the LCI data according to the chosen methodology. The LCI data is usually so complex in terms of the number of emissions that comparing them between different products or systems in any meaningful way is virtually impossible. To make LCIs for different products comparable, the software calculates the cumulative emissions along the supply chain according to the reference flows of the system and then converts the emissions to impacts using characterisation factors. For example, there are many GHGs which have varying effects upon global warming. The software converts the emissions in each category to a single emission equivalent, in the case of GWP, this is carbon dioxide equivalents. 1kg of methane emissions is calculated according to its "characterisation factor" as having the same GWP as 28kg of carbon dioxide over 100 years according to characterisation models provided by the Intergovernmental Panel on Climate Change (IPCC, 2013) 2013). Other emissions are characterised to other impact categories in the same way according to characterisation factors for each emission and impact category. In some cases, a single emission may contribute to more than one impact category, but as a mid-point assessment is made on the potential to cause impact, which is not considered double counting. Some of the most common characterisation factors for impact categories are given in Table 2, although other methods use different factors.

The impact categories included, depend on the assessment method and practitioners may also develop their own user-defined categories, depending on the goal of the LCA. This is the case with the EISI where several other indicators have been used to measure aquaculture-specific impacts. One such example being FishIn: Fish Out ratios (FIFOs) which have commonly been used to assess the use of marine ingredients in aquaculture systems. The indicators that have been developed will be fully discussed in Section 6.

After characterisation into impact categories, there are several optional steps which may be taken. Firstly, impacts may be normalised against a standard. E.g. the impact category results may be presented as a proportion of regional or global impacts or against industry totals. The objective is to provide a better understanding of the relative importance of the emissions including between different impact categories.

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Table 1.2. Common characterisation factors frequently used LCA impact categories

Impact category	Characterisation model	Reference	Characterisation factors
Global Warming Potential $kgCO_2eq$	GWP 100, CML 2001 Baseline	IPCC 2013	CO_2 = 1 CH_4 = 28 N_2O = 265
Acidification Potential Kg SO_2eq	AP, CML 2001 Non-Baseline	(Hauschild and Wenzel, 1998)	SO_2 = 1 NH_3 = 1.88 NO_2 = 0.7
Eutrophication Potential $KgPO_4^{3-}eq$	EP, CML 2001 Baseline	(Heijungs *et al.*, 1992)	PO_4^{3-} = 1 NH_3 = 0.35 COD = 0.022

Impact categories may be aggregated into a total score or different sets according to the goal of the study. The purpose is to provide more manageable outcomes which can be used for policy making. However, this can sometimes lose the necessary detail over various local and global trade-offs. In the case of the EISI, life cycle and other indicators will be aggregated into environmental, economic, social and welfare categories. More detail of the scoring and aggregation procedure will be given in Section 7. Weighting is another optional step in LCA where certain categories are given precedence and this may be partially dictated by the aggregation step previously. In the EISI, the impacts will be aggregated and weighted so that the four broad assessment categories have equal importance overall. The survey that is being used to collect the data for the EISI has different numbers of questions for each category and in some countries/ systems, some questions are not relevant e.g. between Norwegian salmon and Polish carp. Therefore, indicators will be grouped differently according to their relative importance in each situation. Although weighting often includes value loaded choices, the objective of the weighting procedure is not to assess value judgements but to make the EISI equitable between species and considering that the EISI's first objective is to provide a benchmark against which innovation can be compared, value judgements should not be an issue. Details are given in Section 7.

4) Interpretation

Results may be interpreted at various levels of resolution and at various stages during the life cycle, before and after optional stages such as weighting and normalisation. Typically, the results may be interpreted to compare between and within the systems under study. Firstly, as a benchmark, results may be compared in absolute terms, for example in the case of GAIN the GWP of producing salmon to the industry average, compared with salmon produced according to the innovations within the project. Secondly the contributions of various parts of the life cycle may be compared, often termed "contribution" or "hot-spot" analysis. This is especially of interest to GAIN to see the relative importance of the innovation within a life cycle for reducing impact.

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The results may also be subjected to uncertainty analysis, where there is a large variance in the data and to sensitivity analysis where certain inputs may be altered. Sensitivity analysis may be according to the type or quantity of an input, such as changing the electricity mix to incorporate more renewables or by changing the overall input by e.g. 10%. Such analysis allows for more direct comparison between different products where some inputs can be standardised to concentrate on the effects of the areas of interest in the systems. The overarching goal of these analyses is to evaluate the results for completeness, robustness and consistency to enable better conclusions and recommendations.

Section 2. Aquaculture systems studied within GAIN

2.1 Norwegian salmon

The Norwegian salmon industry is the largest fin-fish aquaculture industry in the EEA at over 1.1 million tonnes of production. It is well consolidated with a few large producers, owning many sites and some smaller producers with less than ten sites. Production is almost exclusively in marine cage suspended net pens linked to floating barges, except for smolts which are produced in freshwater “flow through” or Recirculating Aquaculture Systems (RAS). RAS typically allows better control and the ability to produce much larger smolts which are physically more robust before they go to sea. Production is intensive, with high feed inputs, although stocking density has been reduced in recent years for welfare and performance reasons. The grow-out time is usually around 18 months to 2 years, depending on the size of the smolt at stocking. Primary processing (evisceration and bleeding) typically occurs in facilities close to the production centres, but much of the secondary processing to fillets and other products, occurs outside of Norway. Feed is produced in feed mills across Norway, sometimes to the specification of the farm, but usually by one of three large multinational feed companies. In addition to these three main contributors to the Life Cycle Inventory, there are separate well-boat companies that move live fish from smolt facilities to marine grow-out to processing and also carry out some sea-lice treatments. There are also companies that recycle aquaculture equipment and hauliers who transport live or processed fish. Salmon systems are generally highly controlled with various sensors, monitoring water quality, cameras to inspect the fish, and farm management software that allows for precise feed inputs and record keeping.

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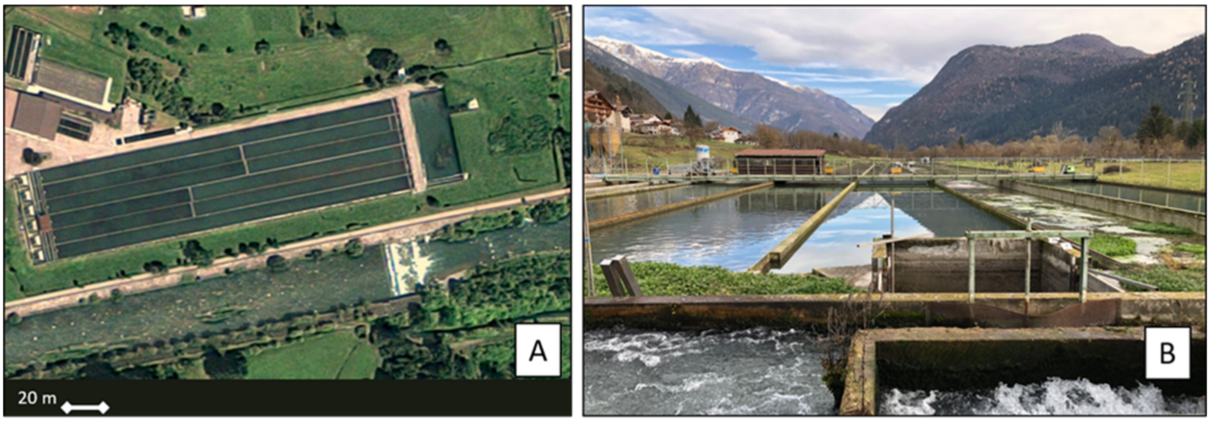
2.2 Italian trout

Italy is a leading rainbow trout (*Oncorhynchus mykiss*) producer in the European Union, with 40,000 tonnes a year, it represents 19% of EU production and exceeds 100 million euros per year average market value (Parisi *et al.*, 2013; STECF, 2019; Maiolo *et al.*, 2021) (although Norway is also major EEA contributor to EU supply). 78% of Italian trout companies are based in the North of the country, with Veneto, Friuli Venezia Giulia, and Trentino - Alto Adige home to 70, 68, and 58 companies, respectively (Fabris, 2012; Maiolo et al., 2021). The pilot site selected for GAIN's activities is located in the autonomous sub-region of Trentino (Service et al., 2019). Small-sized fish (below 500 g) are usually produced to be sold as head-on-gutted (HOG) trout. Larger individuals (ranging between 500 g up to 2 kg) are grown to be processed into e.g. fillets, hamburgers, fish skewers, etc. (Fabris, 2012; Maiolo et al. 2021).

Italian trout production usually happens in monoculture flow-through plants, consisting of either concrete raceways or earthen ponds (Figure 2.2) (Maiolo et al., 2021). In Italy, 20 large companies (6%) control 60% of the national production, selling both whole fish and processed products (ISMEA, 2009). In such entrepreneurial production, we might presume that automation is fostered, and centralised management operated.



After gradually increasing from the 1960s, peaking in 1997 with over 50,000 tonnes a year (Iandoli & Trincanato, 2007), Italian trout production has decreased due to market saturation and produce depreciation (Roncarati & Melotti, 2007). Trout farm production presents several sustainability challenges. A recent review (Maiolo et al., forthcoming) of scientific literature showed that the performances of farmed trout production are quite close to those of farmed salmon. According to Clune et al. (2017), trout production averagely yields slightly higher climate impacts than chicken production, but significantly lower impacts than any mammalian livestock production (e.g. lamb and beef). Philis et al. (2019) report that a complete overview of the environmental sustainability aspects of trout farming is still lacking since: (i) trout production exhibits variable systems and technologies (e.g. flow-through vs. recirculation; management practices; etc.).

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2.3 Polish carp

Carp production in Poland is typically in large extensive or semi-intensive pond systems with low stocking densities and few inputs, with a total production of 20751 MT in 2018 (FAO, 2020b). This production approach is characterised best environmental practices, high level of biodiversity, preservation of natural resources, supporting rural development (Guiseppe and Mente, 2019). They are often cultured as polycultures of several cyprinid species, although the dominant species is common carp (*Cyprinus carpio*). Periodic grading takes place in order to sustain growth. At the start of the winter, carp are transferred to a special pond, in which they reduce their activity and feed intake. The spring of the third year, carp are moved to large ponds, where their natural feed is supplemented with pellets. Feed inputs tend to be of mixed grains and commercially produced pellets. Feeding is usually from demand feeders which the fish can acquire feed by nudging a stick, so that they are fed to their own requirements. Harvest is often in December for the traditional Christmas market, typically 1.5 kg per specimen, sold live. However, a change in consumer perspective has been observed, with increasing processing. Nevertheless, live sales still dominate marketing of the species.

2.4 Spanish seabass and seabream

Although the project set out to benchmark Spanish systems, it was not possible to collect data because of COVID travel restrictions. Only data from nutrition trials was modelled.

2.5 UK oysters and mussels

There are 28 active aquaculture producers in Northern Ireland (NI), employing some 130 people. The main shellfish species cultivated are subtidal mussels and intertidal oysters on trestles (smaller amounts of scallops and Native oysters are also produced, the latter not true aquaculture); and finfish species: marine salmon, fresh water rainbow trout and brown trout. The combined aquaculture industry is valued at approximately £11.6 million (DAERA, 2018). In 2018, the Salmon sector was worth

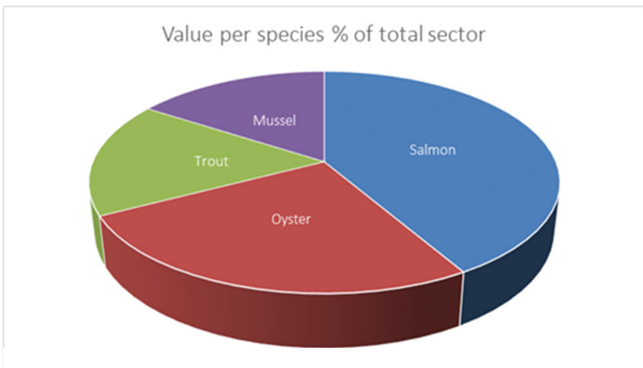

Figure 2.1 Aquaculture Industry in Northern Ireland

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£4.86m (42% of total sector), Oyster sector £2.97m (26%), Trout sector £1.9m (17% of total sector), and Mussel sector £1.84m (16%) (Figure 2.1).

A shift in the main species cultivated has been noted over the last 5 years, from mussels to pacific oysters. Mussel production has dropped from 3324t in 2013 to 2060t in 2018. (price per tonne has also dropped from £1730/t to £891/t). Whilst Pacific oyster production has grown from 138t in 2013 to 909t in 2018. (price per tonne has increased from £2503/t to £3278/t) (Figure 2.1 and Table 2.1). Mussels are dredged from offshore naturally occurring seed beds (Amounts collected are controlled by DAERA), seed mussel is relayed (Figure 2.2) on licensed aquaculture sites in the five sea-loughs (Figure 2.3). Maintenance of bottom grown mussel sites includes: consideration of stocking density; thinning out of mussel density and predator control (mopping for starfish and potting for crabs) as required.

Table 2.1 Shift in main species cultivated in Northern Ireland

Year	Oyster	£ / tonne	Year	mussel	£ / tonne
2013	138t	£2,503	2013	3324	£1,730
2018	909t	£3,278	2018	2060	£891

Figure 2.2 Left to right,, mussel seed, mussel dredge (with mops for predator control) and mussel dredgers.

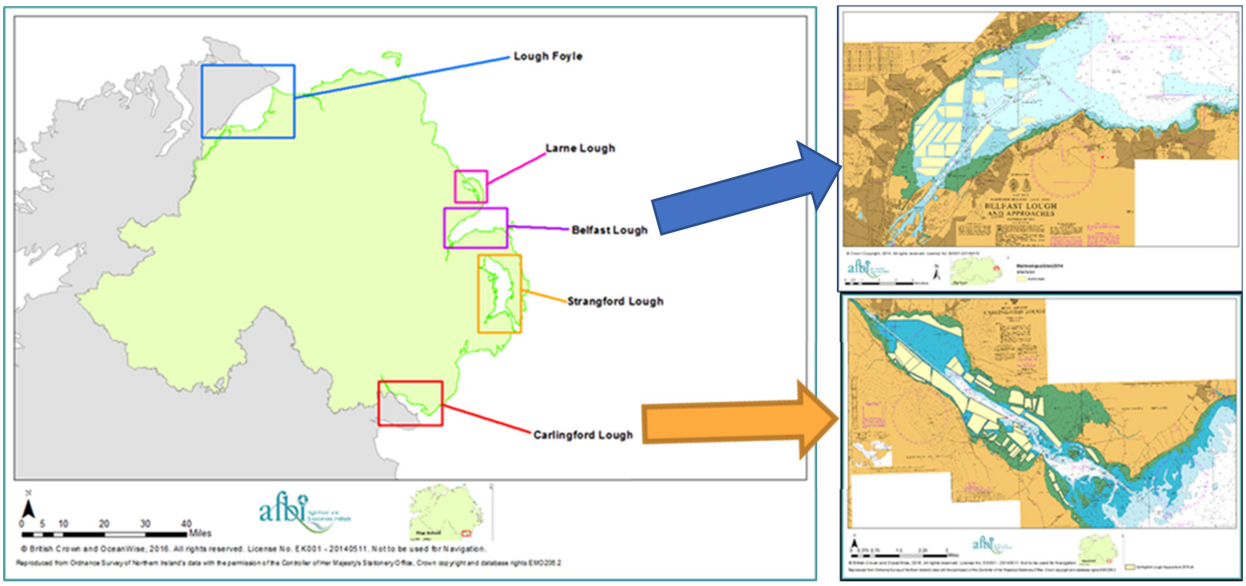

Figure 2.3 Map of five sea-loughs, three Northern Irish, two transboundary. Detail shown of Belfast and Carlingford Loughs, where polygons represent aquaculture sites.

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Oysters are grown from spat which is imported from certified hatcheries, spat is placed in bags (pouches) on intertidal trestles (Figure 2.4) and on-grown to harvestable size (2.5 – 3 years). Oyster site maintenance is required, turning bags to reduce fouling and splitting bags as the oysters grow to maintain good shell shape and growth.

Figure 2.4 Pacific oysters cultivated intertidally on trestles.

Section 3. EISI indicators and data requirements

Development of the EISI indicators was subject to several periods of internal discussion, drawing on the expertise of T4.3 and GAIN members involved in environmental, welfare and socio-economic issues, followed by wider consultation within the GAIN project consortium. Indicators were first drawn up between the UoS and UNIVE based on the LCA framework. Further indicators were added to include more aquaculture specific sustainability issues for environment, welfare, economic and social impact. Consortium opinion was sort at the Typical Farm Workshop (Feb 2019), as described in Section 4. At all stages, indicators were considered for their relevance to EU aquaculture and to the ease of data collection. Indicators were only considered where data would be readily available from the various stakeholders, rather than requiring them to undertake extra activities or excessive investigation. A description of the final indicator set is given below.

Although every effort was made to collect data on all of the indicators included, it was expected that it would not be possible for some species and that not all indicators would be relevant. For example, feed data and most welfare data are not relevant for shellfish species. After data collection, indicator data was aggregated, weighted and normalised to provide a species, context specific index for each species.

3.1 Environmental indicators

Environmental indicators were primarily included based on the CML (Institute of Environmental Sciences, University of Leiden) Baseline assessment methodology, but also include aspects of local impact, including benthic enrichment, chemical use and efficient use of marine resources, for example. A brief description of the indicators is given below.

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3.1.1 Global Warming Potential (GWP)

Global Warming Potential (GWP) is the potential for Greenhouse Gases (GHGs) to affect the temperature of the planet through radiative forcing, i.e. they change the energy balance between the energy of the sun entering the atmosphere, ant that reflected back. The most common and well known GHG is carbon dioxide but it is not the most potent, however, because of the relative contribution to global warming, GWP is interchangeable with "Carbon Footprint". The other most important GHGs in terms of contribution are methane and dinitrogen monoxide (nitrous oxide). The characterisation factors for these GHGs were given in Section 1. Dinitrogen monoxide is important in agricultural systems because of emissions from managed soils which can be heavily affected by the soil type and fertiliser application. Similarly, methane is important in agriculture because of enteric emissions from cattle. Therefore, the use of agricultural feed ingredients within aquaculture can have a large effect on the overall LCA. Climate change through global warming is considered one of the biggest challenges to humanity through sea level rise, increased disease vectors, drought and not least, many factors leading to food insecurity. A few degrees rise can tip the balance of substantially increased crop failure in worst case scenarios but is predicted to make reduced yields of major crop species commonplace.

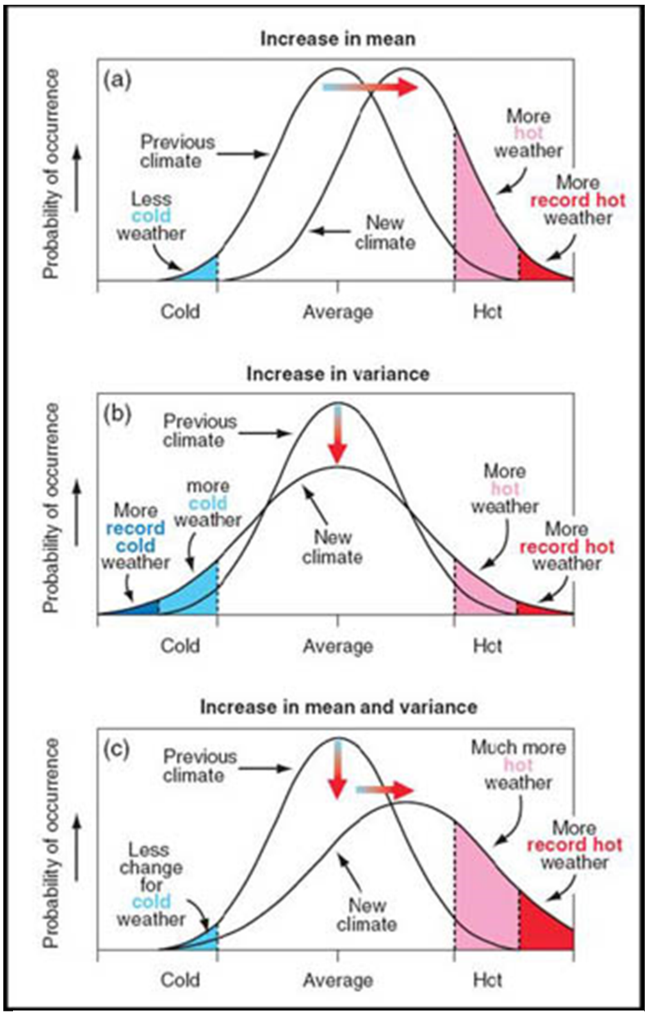

Figure 3.1 Shifts in the distribution of cold and hot weather due to climate change

Source: Walsh (2010)

3.1.2 Acidification potential (AP)

The most common acidifying emissions are from the burning of fossil fuels for energy provision, including sulphur dioxide, nitric oxide and nitrogen dioxide (NO_x), but not dinitrogen monoxide. Ammonium gases also lead to acidification, primarily released by volatisation of nitrogen from managed soils. These emissions are important pollutants leading to acid rain which have caused deforestation, damage to aquatic ecosystems and to building infrastructure (Guinée *et al.*, 2002).

3.1.3 Eutrophication potential (EP)

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Eutrophication is the enrichment of waterbodies with nutrients, particularly nitrates and phosphates, so that the constituents of ecosystems may be affected, the water becomes unpotable or in the worst cases even unsuitable for industry. Eutrophication is measure in phosphate equivalents, although the limiting nutrient is different between freshwater and marine environments. The carrying capacity of a water body to absorb eutrophication is affected by many factors, such as the size of the water body, current speeds, rainfall etc. The nature of supply chains within LCIs mean it is unlikely that a high level of contextualisation is possible.

3.1.4 Fresh water consumption (CWU)

Freshwater use impact categories are also becoming increasingly used in LCAs, although they have not been widely used within aquaculture LCAs. Particularly in aquaculture, a distinction should be made between water that is used and returned to the environment compared to that which is consumed within the process and is not readily available for further use. Aquaculture is *dependent* on large quantities of water in many pond and tank based systems for the environmental services it provides (primarily dissolved oxygen and waste dilution). However, this is often returned to the watercourse without being consumed, although it may be eutrophied or affected in some other way. Previous LCA studies have shown that the most important contribution to water use is from growing crops to provide feed. In the case of the EISI, we are only interested in water that in consumptive water use (CWU) as pollution factors are accounted for in other indicators. The importance of water withdrawal is specific to location and some water foot-printing methods (e.g. AWARE) attempt to factor in location specific scarcity factors. In the GAIN project, the CWU is not adjusted for scarcity because no other indicator has that level of resolution. By using scarcity factors for one indicator it effectively weights it more than other indicators in the index. It is possible to match scarcity factors provided within the AWARE methodology separately using the water withdrawal to availability ratio (WTA) or Water Stress Index (WTA*) (Pfister *et al.*, 2009; Berger and Finkbeiner, 2010) at any point for contextualisation provided the location of the water use is known.

In LCA methodology, it is common to split water use into different categories. Green water is precipitated or present in the soil, blue water must be extracted from surface or groundwater supplies and grey water is that needed to dilute emissions and return degraded water to specific quality standards (Berger and Finkbeiner 2010). The EISI combines blue and green water into CWU as a single category based on the requirements of crops given by Brouwer and Heibloum (1986) and Mekonnen and Hoekstra (2011). This is because extraction and rainfall varies temporally and geographically, but the requirement remains broadly within the same range. In the case of grey water, the quantity required to return water to its natural state or specific requirements is likely to be highly variable, depending on the volume of the receiving water body and its initial state.

3.1.5 Coastal Sea Area

Despite no direct consumptive use of freshwater, mariculture systems require marine current to provide the ecological services to maintain a healthy stock. In some locations such as Norwegian and Scottish coasts, lack of appropriate sites is a constraint to the continued expansion of the industry and in China, the large number of operational sites has led to serious water quality concerns in some areas.

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Therefore, the quantity of coastal surface sea area was considered a relevant indicator for mariculture systems within the GAIN project.

3.1.6 Land use

Approximately a third of agricultural crop land use is devoted to the production of feed ingredients (Robinson *et al.*, 2011). Despite improvements in crop yields, deforestation and degradation of land through expansion of agriculture is a continuing threat, linked to alarming biodiversity loss. Land use (LU) and Land use change (LUC) are both of increasing interest to quantify within LCAs. However, LUC remains divisive and difficult to quantify (Milà i Canals *et al.*, 2006). Contention concerns the environmental services provided before and after transformation such as carbon sequestration and the impacts on biodiversity due to habitat loss which are difficult to quantify. For those reasons, only LU is included in the EISI, rather than LUC. The land use can be contextualised according to geography and interpreted according to where the most sensitive land use occurs, such as areas which have received criticism for habitat loss. Similarly, to CWU, the majority of land use is linked to the provision of feed ingredients, apart from extensive, non-fed systems. Therefore, it can be quite geographically distinct from the production site. Of particular interest is the land use related to soybean, often linked to deforestation in Brazil which has concerns over loos of biodiversity, displacement of indigenous peoples, release of GHGs through burning, loss of vegetative biomass and mineralisation of soils and loss of CO_2 sequestration (Nguyen *et al.*, 2010).

3.1.7 Economic Fish in: Fish out Ratio (eFIFO)

Aquaculture has been heavily criticised for its impact on marine fisheries to supply marine ingredients in aquafeeds (e.g. Naylor *et al.* (2009)). While some of this criticism is exaggerated and misplaced, particularly mariculture, still consumes significant quantities of fishmeal and fish oil. Meanwhile global supplies of marine ingredients have decreased gradually over time so that aquaculture has taken an ever-larger share (Shepherd and Jackson, 2013). While there is considerable opportunity for directing fishery processing by-products to marine ingredients, now contributing a third of supplies (Jackson and Newton, 2016), the additional volumes have not resulted in an overall rise in global supply. The aim of the GAIN project is to promote circular economy principles so that reuse and recycling of valuable nutrients is promoted. The eFIFO methodology partitions the impacts of production between co-products based on their economic value so that low value by-products carry lower embodied impact than principal co-products such as fillets. Therefore, marine ingredient inputs from by-products will likely have a lower footprint than marine ingredients from dedicated reduction fisheries. The economic allocation also attributes burdens between rendered oil and meal on an economic basis so that usually oil will carry a larger burden as the more limiting and expensive co-product.

3.1.8 Biotic Resource use (BRU)

Some LCA studies measure the use of marine ingredients and other biotic resources with the Biotic Resource Use (BRU) metric (sometimes referred to as Net Primary Productivity appropriation, NPP), measured in kg of carbon accumulated through the food chain. BRU is calculated from the C content

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of the feed marine ingredients adjusted to the trophic level of the biotic resource according to methodology reported by Pauly and Christensen (1995) using trophic level data from the Fishbase website (https://www.fishbase.de/). We have also included the BRU associated with land clearance and LUC in some cases, but the calculation only includes appropriation from nature and therefore does not include cultured plants unless their supply chain includes biotic resources from the biosphere. The method is criticised because it takes little account of the sensitivity or status of the natural resource and therefore may be considered as less appropriate than FIFO which is more recognised within international certification standards.

3.1.9 Cumulative Energy Demand (CED)

There have been several different approaches to Cumulative Energy Demand (CED) calculations as discussed by Heijungs and Frischknecht (2004). Most fundamentally, considerations are around what energy sources are included and whether the calculations included the embodied energy within the raw material/energy resource or just the energy provided to the user. In many cases, LCAs that include CED have only considered non-renewables (e.g. Table 1.1) including the energy content of the raw material, thus factoring in the efficiency of conversion to the user. Doing so, provides a case specific LCA that is not transferable between regions that use different energy mixes. As the purpose of the EISI is to provide a benchmark against which innovations can be tested and which is highly transferable, highly case-specific outcomes are not desirable. For that reason, the CED category included within the EISI measures the energy demand of the user, but separated into renewable and non-renewable sources depending on the energy mix of the supply chain.

3.1.10 Energy Return On Investment (EROI)

Energy Return On Investment (EROI) is directly related to CED in that it measures the ratio of CED to the energy content of the product. EROI was initially developed for the energy sector, but has since been applied to food systems, in which case EROI is usually determined for the edible portion of the functional unit. In the case of the EISI, we also consider the energy content of by-product streams for further application at the processor gate. The EROI is therefore the energy content of the aquaculture product divided by the CED to processor gate.

3.1.11 Benthic Impact (BI)

Benthic impact is a concern for cage-based farming in lakes and coastal areas. It is caused by the build up of waste feed and faeces from aquaculture activities where currents are not adequate for effectively dispersal. The build-up leads to organic enrichment which can cause anaerobic processes and affect the biodiversity around the site. The amount of deposition in $g/m^2/yr$ is calculated according the methodology of Gillibrand *et al.* (2002) that measure the rate of sedimentation as a function of current speed, depth and the feed supplied.

3.1.14 Environmental impact checklist indicators

In addition to the measurable indicators above, the EISI includes a checklist of several non-measurable parameters. These include; certification, record keeping, use of antibiotics and chemical therapeutics,

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and environmental mitigation methods. The checklist is a dimensionless, binary response (i.e. presence or absence), rather than putting any specific measurement upon the parameters. The indicators are then calculated as a percentage of the industry that is meeting the necessary requirements of the indicator. In the case of water quality and welfare checklists, these are also expressed over a timeframe.

3.2 Economic indicators

Life Cycle Costing (LCC) is a measure of the financial flows through the life cycle of a product and is not a new concept. However, LCC does not represent all of the economic feasibility and sustainability issues of an industry and is not specific for the aquaculture industry. The EISI endeavours to capture economic sustainability indicators which affect aquaculture and can be used to benchmark against the GAIN innovations. Economic sustainability indicators are difficult to collect because it involves asking companies for highly sensitive information about the cost and revenue flows within the business. Several indicators have been included that rely on various levels of economic data from producers, but response is expected to be limited in the case of the most sensitive information. With this in mind, several indicators were designed in a way that they would not require sensitive cost information and that could be applied from a whole value chain perspective. Owing to the difficulty in acquiring data and the sensitivity of the data, the economic indicators are largely restricted to primary data that could be collected from the farm and processing only. An outline of the indicators is given below.

3.2.1 Processing quality assurance (PQA)

How many parameters are used to assess the quality of fish leaving the processor gate? The data usually includes size, colour, freshness, gape etc. The number and consistency of the different parameters gives an indication that processors are striving for high quality products which makes the company competitive and resilient to economic shocks.

3.2.2 Fish rejection at processor (FRP)

The volume and percentage of fish rejected at the processor for various reasons. Common reasons are damage to fish due to processing machinery or from lice. The data provides another level of quality assurance and is an indicator that both production and processing are efficient, up-to-date and well maintained.

3.2.3 Feed efficiency (FE)

Although feed efficiency is commonly viewed as an environmental issue, feed commonly accounts for the majority of input costs to fish farms. Keeping the economic Feed Conversion Ratio (eFCR) within industry norms makes demonstrates a required level of efficiency that will contribute to competitiveness.

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3.2.4 Input cost ratio (ICR)

Data on the cost structure of major inputs, particularly at the farming stage; feed, labour, energy, other costs. The major costs for aquaculture are usually feed and labour and the ratio between the two is also important, depending on the system and species produced. Having a low ratio of labour to other operating costs indicates high productivity and having a high ratio of feed indicates that other operating costs are low and that the production is efficient. Depending on the system and species, it is common for feed to make up between 50% and 80% of operating costs.

3.2.5 Market structure (MS)

This indicator provides information on how much of the product is for domestic and export markets. A large proportion of export volume indicates that the industry is well developed, with a high level of self-sufficiency and able to provide for a diverse range of consumers with large, efficient and competitive companies in most cases. However, some aquaculture industries have been criticised for being too export oriented with negative impacts on local populations, therefore a good balance between import and export is desired.

3.2.6 Market product diversity (MPD)

Market product diversity is a direct measure of the number of different products which are sold and to whom, i.e. retail, hospitality, etc. A large number of products reflects a well-developed industry with high levels of value addition, adding resilience and competitiveness. This is reflected by high levels of processing and good markets for all the co-products. The basis for the scoring is derived from Stevens et al (2018), using salmon as a benchmark of a highly processed species with well established markets.

3.2.7 Mortality Volume (MV)

Stock losses can be considered as an economic, environmental and welfare issue. As an economic and environmental indicator, it reflects the efficiency of production, especially if losses occur towards the end of production when a lot has been invested already. In the EISI, mortality is represented as both an economic indicator in terms of % volume of stock lost during production and as a welfare indicator as % numbers of individual animals lost, but not as an environmental indicator as there are already many more environmental indicators, which incorporate the efficiency of production.

3.2.8 Innovation value (IV)

This indicator is specific to innovation being carried out within GAIN and is a measure of the extra value that the innovation adds to the industry. The indicator depends on the willingness of actors within the value chain to provide financial information and that available within the literature.

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3.3 Social Indicators

Although social sustainability issues are well represented in certification standards, they are not often used in Life Cycle Assessments. There have been efforts to incorporate social impact categories in S-LCA but are not well adopted. Many indicators are concerned with the amount and structure of employment throughout a value chain. However, there are also other important considerations which are more difficult to measure from a life cycle perspective, such as the safety of employees. This data is also more sensitive and therefore difficult to collect, as well as having a degree of subjectivity. In this regard, the indicators are collected as a checklist that ensures that the industry is taking precautions against occupational health risk. Checklists are quantified by the percentage of the industry that meets certain requirements, e.g. X% of the industry have 3rd party certification.

3.3.1 Labour structure (LS)

The labour structure indicator measures the ratio of different types of employees within the industry; full time vs seasonal, men vs women and management vs manual workers. The data provides information on the equitability of the industry and the level of opportunity offered to the workforce. The balance of male/female employment is of particular interest as there is often a large preference for males to be employed within aquaculture production because of the physical nature of the job. However, this may change as working conditions are improved and there are other opportunities throughout the value chain. Using a life cycle approach it is possible to see where the various contributions are weighted.

3.3.2 Labour effort (LE)

Labour effort is a measure of productivity of the workforce. Productivity is a measure of the amount of product produced per full time employee. High productivity indicates highly efficient production systems with high levels of management through the value chain. Total production is measured per FTE.

3.3.3 Employee risk training (ERT)

This is a checklist that all staff have been adequately trained against relevant risk within the company, including use of chemicals, boat safety, machinery etc. This ensures that all staff are aware of the greatest risks that may be encountered and know how to avoid incident.

3.3.4 Employee safety (ES)

This is a checklist that all staff receive adequate equipment to do their job safely and well, including necessary clothing, safety equipment and tools. This is another measure that where risk is unavoidable, the staff are provided with as much protection as possible.

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3.3.5 Certification schemes membership (CSM)

Membership of certification schemes can act as a recognition that the company is adhering to a high level of responsibility to its own workforce and the community in which the business is located. Certification often covers a broad range of social conditions, including access to equitable pay, leave and other entitlements. They also cover restriction of poor practices such as child and slave labour. Therefore, inclusion within certification schemes give a broad indication of social responsibility compliance.

3.4 Animal welfare indicators

Welfare indicators are seldom incorporated into LCA although there has been some research (e.g. Scherer *et al.* (2018)). From a life cycle perspective, incorporation is highly problematic as the welfare of animals indirectly involved in supply chains may also be affected. There may also be welfare issues regarding predator control, such as from birds or seals. The issues surrounding welfare in supply chains and predator control may become highly subjective, sensitive and challenging in data collection. In the EISI, we are only concerned with the farmed animal and how its welfare is affected by farm and processing practices.

3.4.1 Harvesting schedule (HS)

Have the fish been emergency harvested and what is the rate of emergency harvest within the industry? Emergency harvesting is carried out when there is a health management problem that is employed to prevent losses before they occur and is an indicator of welfare problems that may not otherwise be picked up.

3.4.2 Mortality number (MN)

What is the rate of mortality in numbers as a percentage? The mortality rate in numbers is measured against expected industry figures, taking into account higher expected mortality in the hatchery stage compared to during grow-out.

3.4.3 Active body damage observation (ABD)

In salmon culture and some other industries, fish are routinely inspected for active damage to various parts of the fishes' anatomy. Most commonly the fins, gill operculum, eyes, snout and skin are inspected and scored. Significant damage may lead to sites of secondary infection leading to disease if unchecked, as well as causing the fish discomfort. The indicator is a checklist of different parameters against the timeframe in which they are measured (e.g. daily, weekly, monthly).

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3.4.4 Specific growth rate (SGR)

When fish become stressed, growth is often compromised as energy is redirected, therefore attaining a normal growth rate, within expected industry norms, is an indicator that fish are not being subjected to stress. Growth rate in aquaculture is normally measured as the cumulative growth rate over the production period (Specific Growth Rate, SGR), although in practice the growth rate varies considerably in relation to the animals' size and to the environmental conditions, especially temperature.

3.4.5 Slaughter practice index (SPI)

There are various approved methods of slaughter. However, some methods are considered to be more humane such as electro-stunning. Blows to the head given by a machine are also considered humane with methods such as using ice-slurries considered less humane. The live sale of fish has raised concerns over welfare because of the distress of the animal in transit and that slaughter methods are unknown with many thought to suffocate slowly.

3.4.6 Predation prevention measures (PPM)

Predation can cause mortality, wounds which can lead to secondary infection and likely rejection by processors, and stress to the stock. Various non-lethal anti-predator methods are available such as acoustic seal scarers, various traps and anti-bird netting. The indicator will list the number of predation threats and the methods used to prevent predation.

3.4.7 Stocking density (SD)

Stocking density has long been considered a key welfare issue within aquaculture. Although the general perception is that lower densities are better for fish welfare, it is highly species specific. As shoaling animals, if stocking densities are not optimised (i.e. are too low or too high), fish can become territorial, hierarchical and lead to aggression. This is especially the case with carnivorous species although hierarchies do also develop in herbivorous species (e.g. tilapia). Therefore, it is important to optimise densities to avoid stress and damage to fish. Optimum stocking densities for welfare are published by certification agencies such as the Soil Association (2021).

3.4.8 Fish welfare training

Proper fish handling is essential to maintaining fish welfare. This includes, netting fish from tanks and cages, holding fish properly, moving fish between tanks and cages, dispatching moribund or injured fish etc. The indicator is a checklist that staff have been trained in appropriate fish handling techniques.

3.4.9 Health Management Checklist

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The health management checklist includes information about measures that farms take to ensure that the stock is being well cared for. It includes checks around frequency of routine veterinary checks, vaccination protocols and stock observation.

3.5 Cost-benefit analyses: typical farm approach

For full economic cost-benefit analyses of eco-efficient production practices, the typical farm approach (TFA) was applied within T4.1 as a baseline for farm-level predictions (see also Kreiss and Brüning, 2020, D 4.1). TFA is an engineering approach offering a standardized sampling and data collection strategy for model farm economic datasets, that are empirically grounded (Isermeyer 2012, Walther 2014). The method was developed by *agri benchmark* (see also agribenchmark.org) and combines focus groups, expert interviews, and farm observations to define representative farm datasets for selected production regions. Expert focus groups with key stakeholders from research and business sectors build the core element and the resulting farm-level economic datasets are validated discursively for their coherence and allow a high detail of microeconomic analysis (see Lasner et al. 2017 for more details). Within GAIN, existing and updated datasets were used as baselines to estimate the costs and benefits of eco-efficient aquaculture production scenarios e.g. for novel feed formulations.

Section 4. Stakeholder and expert consultation

The Stakeholder and expert consultation over the EISI occurred in three phases.

4.1 Phase 1. Internal consultation

The first phase of the index development started in Autumn 2018, when internal discussions took place between environmental, social science and welfare specialists from University of Stirling (UoS) and University of Venice (UNIVE) to begin drawing up the list of indicators. Environmental indicators include typical Life Cycle Assessment impact categories, strengthened by aquaculture specific indicators drawn on the knowledge of UoS work in aquaculture impact assessment. Socio-economic indicators were developed from Valenti *et al.* (2018) and the extensive experience of the UoS working in aquaculture development and certification. However, it was accepted that it would not be possible to undertake a high level of socio-economic work within the community and the indicators relate only to the performance of the aquaculture enterprise and its responsibility to its staff, rather than wider Corporate Social Responsibility (CSR). The initial indicator list that was first discussed between relevant partners is shown in Table 4.1.

Table 4.1 Initial list of EISI sustainability indicators under discussion within GAIN T4.3

Theme	Indicator name	Indicator criteria
Econ.	**Productivity**	Total productivity of innovation (i.e. ratio of output value to inputs).
Econ.	**Innovation**	% Value add to industry of innovation.

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Econ.	**Economic return**	IRR/NPP of innovation.
Econ.	**Development**	Time to development of equipment/ infrastructure.
Econ.	**Integration**	Polyculture/integration: proportion of land/sea area devoted to agriculture vs aquaculture - ratio of component to income.
Econ.	**Input efficiency**	Total value per unit input (feed,energy,labour etc).
Welfare	**Mortality**	What is the survival rate?
Welfare	**Stress fin**	Fin score index
Welfare	**Stress behaviour**	Stress related loss in appetite ? Number of events??
Welfare	**Gill condition**	Gill condition index
Welfare	**Growth rate**	How close to expected SGR
Welfare	**Condition**	Body condition index
Welfare	**Flesh pH**	
Welfare	**Slaughter practice score**	Adequate stunning, recovery rate… needs to be collected separately.
Welfare	**Stocking density**	SD scoring
Welfare	**Health checks**	Number of vet visits
Envir.	**Hazard**	Does the innovation pose an environmental hazard regarding the use and discharge of chemicals?
Envir.	**Chemicals**	Does the innovation conform to EU regulatory criteria (WFD and or MSFD) for source waters and chemical and nutrient discharges?
Envir.	**Ammonia**	total ammoniacal nitrogen (TAN)
Envir.	**Phosphorous**	total phosphorous - conforms to EU standards - within assimilative capacity of ecosystem - meets WFD citeria.
Envir.	**Oxygen demand**	BOD/COD -
Envir.	**SS**	Suspended solids in water column
Envir.	**Benthic impact**	Benthic impact
Envir.	**Mortality**	kg % farm mortalities to production
Envir.	**Product utilisation**	proportions of whole product going to human or livestock consumption, other uses or disposal after processing - Hierarchy of efficiency of product utilisation.
Envir.	**GWP**	Volume of CO2-emissions from enterprises along the value-chain.
Envir.	**CWP**	Fresh water consumption footprint and water dependency.
Envir.	**AP** (Acidification Potential)	Level of acidification emissions as a result of enterprises along the value chain.

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Envir.	**EP** (Eutrophication Potential)	Level of eutrophication of water bodies as a result of enterprises along the value chain.
Envir.	**LU**	Land footprint
Envir.	**Coastal sea area**	Area of sea used within a certain boundary…to be determined.
Envir.	**Feed efficiency**	eFCR, PER, NPP
Envir.	**FMDR, FODR**	Fish meal and fish oil dependency ratios, excluding fish meal/oil from by-product sources (FIFO), Biotic resource use kg C.
Envir.	**EROI**	Energy return on investment (all energy inputs; chemical, electricity, heat etc)
Envir.	**Capacity**	Over maximum allowed stocking (could be welfare issue).
Social	**Food safety**	Does the innovation comply to food safety management via a HACCP-based risk assessment implemented during processing?
Social	**Traceability**	Does the innovation comply with current traceability and legislation implementation by national and EU authorities.
Social	**Consumer safety acceptance**	Level of consumer acceptance based on survey work (safety).
Social	**Consumer sustainable acceptance**	Level of consumer acceptance based on survey work (environment)
Social	**Consumer social acceptance**	Level of consumer acceptance based on survey work (responsibility)
Social	**Labour effort**	Labour productivity (ratio of output value to persons employed).
Social	**seasonal employment**	proportion of FTEs to seasonal
Social	**Employee risk**	Use of hazardous chemicals/equipment
Social	**Employee safety**	Do workers have access to the necessary equipment to perform working tasks safely?
Social	**Certification**	Conformation with international standards - ASC/GGAP/BAP etc.

After several rounds of discussion between participants in T4.3, a final list of appropriate indicators was drawn up for the species under study in terms of representativeness and ability to collect the data. The list of indicators was presented at the Typical Farm Workshop for phase two of the index development.

4.2 Phase 2. Screening by GAIN consortium

In February 2019, the Typical Farm Workshop was held in Bremerhaven, led by Thuenen Institute, to prepare key GAIN partners for the Typical Farm data collection. The overlap between the Typical Farm work and EISI work provided an excellent opportunity to incorporate the principles of Life Cycle

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Assessment, Value Chain Analysis and sustainability index work within the workshop. An afternoon session was held within the workshop to prepare partners for the VCA and EISI work.

The session was held in two parts. The first part was held for partners to help LCA practitioners understand aquaculture value chain better. The attendees were split into groups representing the GAIN species so that partners from producer countries were placed on the relevant species group, e.g. members from CSIC were put on the seabass and bream group, attendees from GIFAS on the salmon group etc so that all the main finfish species were represented. The groups were handed flow charts of the main relationships within the value chain for their species and asked to make corrections and comments to aid the development of VCA and EISI surveys (Figure 4.1). Presentations were given by Silvia Maiolo (UNIVE) and Wesley Malcorps (UoS) on LCA and VCA respectively (Figure 4.2) to provide the attendees with an overview of the methodology that underpins them and that would be used to construct the EISI. Richard Newton of UoS gave a presentation on the expected sample frame for the data collection and what was requested from local partners to facilitate data collection for their respective species value chains.

Figure 4.1 Flow chart exercise to determine value chain linkages in EU aquaculture

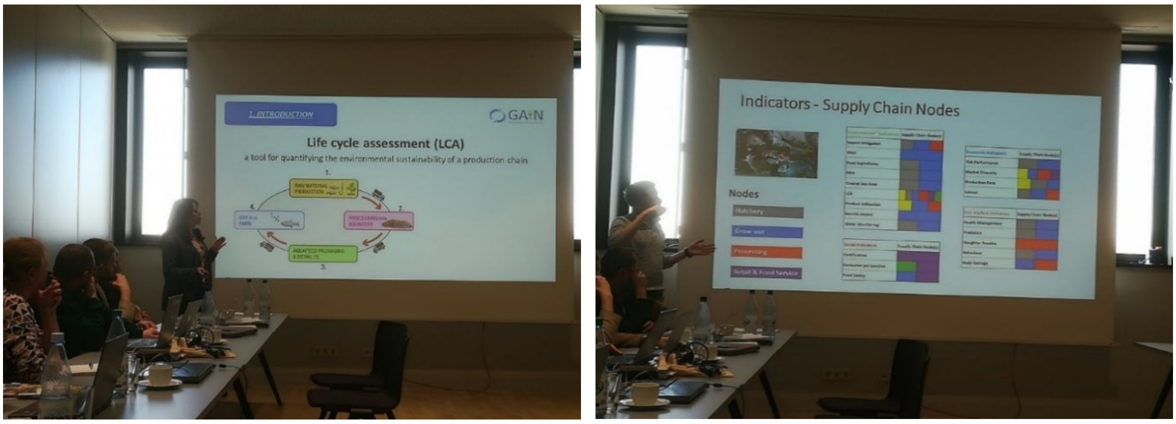

Figure 4.2 Presentations given by Silvia Maiolo and Wesley Malcorps on LCA and VCA at the Typical Farm Workshop, Bremerhaven, February 2019.

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Following the presentations, attendees were requested to work in the same groups to evaluate the proposed EISI indicator list on its relevance to their species value chain and on the accessibility of the data from stakeholders (Figure 4.3). Generally, most indicators were deemed to be relevant to all species but there could be some issues with data collection in some cases. Body Condition Index was dropped as an indicator because the length of fish was not measured and adherence to certification "major musts" was changed merely to certification scheme membership because a lot of the data required for certification is confidential. A few indicators were obviously only relevant for some species such as Coastal Sea Area Use and subsequently considered candidates for deletion from the EISI. Following the exercises, the results were collected and adjustments to the indicator lists were made prior to piloting in-country.

Figure 4.3 EISI indicator relevance and accessibility group exercise

4.3 Phase 3. Post data collection weighting by stakeholder engagement

After data collection and cleaning, indicators were assessed for their reliability and proximity to other indicators was tested using a combination of sensitivity, correlation and principal component analysis (PCA). Those results were then used to inform upon the weighting procedure in combination with stakeholder perception. Correlation and PCA provides information on how closely linked different variables are according to their distribution and how they change in response to changes in different variables (sensitivity analysis). Closely linked variables could be aggregated more closely within the indicator matrix or some deleted entirely if they are considered to "double count" a certain issue. Key stakeholders from the VCA and LCA data collection process were contacted for their perceptions on the importance of different indicators by giving scores from 1 to 8 on each indicator. The scores were used to provide information on the relevance of different indicators to the different aquaculture industries studied within GAIN, which were then used to weight the individual indicators.

Section 5. GAIN research questions

The research questions, introduced in Section 1 relate to various types of innovation within European aquaculture value chains. Innovation is not limited to technology, but may also be structural or managerial in nature and may be incremental or radical. Types of innovation and their effect on aquaculture value chains are described by Joffre *et al.* (2017).

The types of innovation priorities and their impact on the various aquaculture value chains are different. Well established, intensive, consolidated salmon production is evolving due to technological innovation, whereas in Poland, carp value chains are attempting to apply structural changes in terms

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of different product forms and markets. All of these innovations can affect sustainability and are therefore incorporated into the research questions for both VCA and LCA. The questions that affect the EISI directly are included within this section and discussed in more depth with respect to the EISI indicators. With respect to the research questions outlined in section 1.3, the EISI contributes most to answering three research questions around technical and structural innovations

i. **Technical Innovation**

- Which innovations are likely to result in long-term sustainability benefits to the EU aquaculture industry?

There are various innovations which are being considered within the GAIN project from feed ingredients, through precision aquaculture at grow out, to post-harvest value addition to by-product streams. The technical innovations within GAIN are briefly described below, along with which EISI indicators are most likely to be affected.

Table 5.1 GAIN innovations that are being tested with the EISI, species, countries and partners involved (AS – Atlantic Salmon, Oy - Oyster, RT – Rainbow Trout, SBa – Seabass, SBr – Sea Bream, Tu – Turbot).

	Innovation	Species	Country	Partners responsible
a)	Use of novel feeds	AS, RT, SBa, SBr, Tu	No, It, Es, Pt	UoS, UNIVE, Sparos, GIFAS, CSIC
b)	Oxygen supply optimization	RT	It	UNIVE, FEM
c)	Sludge valorisation	AS		UNIVE, SHP
d)	Capture of dissolved inorganic nutrient	AS		UNIVE, SHP
e)	Mortality disposal	AS	No	UNIVE, WAISTER
f)	Use of bivalve shells as filters in RAS	Oy, RT		

a) Innovative feed ingredients produced in WP2 have been produced at a pilot level from aquaculture processing by-products. These are being used within nutrition trials in WP1. The use of the by-products reduces waste from the producer and also reliance on marine ingredients that could come from less sustainable resources. eFIFO is a measure of the efficiency of using marine ingredients so this indicator is most likely to be affected. However, the reduction of waste is also expected to improve most other environmental indicators, including carbon, land and water footprints. However, by-product ingredients are often regarded as poorer quality than traditional ingredients which may lead to poorer water quality around the farm, affecting eutrophication, suspended solids and benthic deposition. This could in turn affect fish welfare.
b) Oxygen is critical for land-based aquaculture production. Its availability within the water column can rapidly change due to a variety of factors, possibly leading to losses. Oxygen

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solubility is affected by temperature so that dissolved oxygen concentrations [DO] are limited as water warms. This can often be overcome using injection of liquid oxygen to "super saturate" the water supply. Fish metabolise oxygen differently depending on several factors too. For example, they use elevated oxygen levels if they become stressed for any reason and during normal digestion processes. Therefore, low oxygen levels can also curtail growth if fish cannot be fed due to low [DO] and affect the quality of wastewater through poor feed efficiency. UNIVE is working with a rainbow trout producer in the municipality of Preore, near the city of Trento to investigate the sustainability implications of oxygen supply on trout performance. The goal is to explore scenarios to optimise oxygen supply, FCR, and feeding time while reducing nitrogen emissions in wastewater. Real-time monitoring of water temperature and dissolved oxygen along with water samples to measure oxidation-reduction potential [ORP], NH_4^+, NO_3^-, pH, and conductivity together with farm management data will inform the analysis. Data will also help correlate farmers' observations about the overall trout welfare with its potential drivers.

c) Recirculating Aquaculture Systems (RAS) are becoming more and more relevant for the salmon industry and its smolt production. In a RAS facility, the effluent is treated through a mechanical filtration process, in order to remove faeces, waste feed, and other particles. Then, the water goes through a biofilter, which converts ammonium into nitrate. Oxygen is supplied in the gas control unit, where excess CO_2 can also be removed. As a last step, the water is sterilised using UV irradiation before being recirculated to the fish tank. About 1–2% of the water needs to be replaced, to avoid nitrate accumulation. The Norwegian plant analysed to which GAIN innovation was applied also includes a thermal unit for adjusting water temperature. In a RAS system, a relevant fraction of nutrients is removed from aquaculture wastewaters, including nitrogen and phosphorus. This happens via a mechanical filter (40 and 80 µm mesh size), removing larger particles and producing a nutrient-rich "reject water", which can be further processed. Salten Havbrukspark (SHP) designed and tested a new S3 filter-dryer system, which significantly reduces the amount of suspended matter in wastewater streams from aquaculture. The S3 filter-dryer, described in detail in (Cristiano *et al.,* 2021) uses a filter cloth with a mesh size of 6 µm, removing 93 $\pm$ 2.8% of the suspended solids from the reject water. In parallel, resulting sludge is dried by an infrared system minimising the respective energy use for sludge drying and transport.

d) The eco-innovations about biofilters consist in reusing mussel shells to replace plastic rings in RAS with biofilters, as outlined in GAIN's deliverables D2.4 (Sousa *et al.*, 2019) and D2.8 (Regueiro *et al.*, 2021) *et al.*, 2021). In particular, shells from Spanish cannery industries on the Atlantic coasts were tested, at a lab scale (TRL 4-5). Three containers were used, whose capacity is 10 L each: two of them were filled with shells (whole and crushed, respectively) and one with plastic rings. The filter filled with plastic rings represents the business-as-usual scenario, and the biofilters filled with whole and crushed shells represent instead the eco-innovations within GAIN. It might be worth to recall here that the main aim of all of these filters is wastewater nitrification" (*ibid.*).

e) Currently, the main technology for processing fish mortality is the ensilage, according to which formic acid is used and hazardous substance disposed of and transported away from the plant (see Baarset & Johansen, 2019). GAIN innovative process aims at drying and sanitising fish biomass using a superheated steam drying technology, with mechanical fluidisation of the product. The process was optimised by GAIN partner Waister, see (Baarset&al2021). The main

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advantages of such innovation lie in the improvements in workers' safety and in overall reduced operational monetary costs (more details in D2.2, Baarset & Johansen, 2019; and in D2.6, Baarset *et al.*, 2021).

ii. Structural Innovation

- How do different systems, scales and managerial approaches affect the sustainability of EU aquaculture operations?
- What factors are most important for the sustainability of different EU aquaculture operations in the face of future scenarios of change, such as globalization, competition, rise in food prices, climate change etc?

Structural innovations are not specifically mentioned within the GAIN proposal, but are outcomes of the VCA work which has been conducted in parallel with the LCA work. An example of structural change is move towards more processed carp in Poland away from live sales in response to welfare issues. While this will undoubtedly improve welfare, it is also likely to have other consequences for impact, in terms of fish transport and the redirection of co-products from processing to different industries. Such innovations will be explored in scenario analysis of Deliverable 4.2.

Section 6. Data models for the EISI

6.1 Functional Unit

The functional unit (FU) is the reference unit against which impacts are measured and therefore adequately defining the FU according to the goal and scope is critical (ISO, 2006a; 2006b). In many aquaculture LCAs the FU has been the liveweight of fish at the farm gate (e.g. Pelletier *et al.* (2009)), which may be adequate for comparing production systems for the same species but is not adequate for the purposes of GAIN. The initial purpose of the EISI is to benchmark industry averages for species and systems within the project. In such circumstances, the most logical choice of FU is a unit (e.g. a tonne) of edible yield. However, GAIN is exploring production of value chains from a circular economy perspective in many cases, therefore the boundary does not stop at the farm or processor gate. Due to the circular nature of the work within GAIN creativity and flexibility is required to apply appropriate FUs to answer the research questions. For example, it is appropriate to set the boundary at the farm gate with a live weight FU to assess oxygen use on Italian trout farms because it is the effect on production that is being explored and all downstream processes (processing etc) can be assumed to be identical. It is not appropriate to have a boundary that stops at the farm gate for investigating the use of processing by-products in feed trials. This is the most complex example because utilisation of salmon by-products in seabream diets and the use of seabream by-product in salmon diets could be considered an example of open-loop recycling, where some co-products are recycled in ever diminishing volumes. The FU for such production systems may be modelled for single products using allocation to determine the impacts of each co-product from the system, or alternatively, the system can be expanded and measured in its entirety such as the collective production of co-products from a processor. The analysis will include a range of outputs from individual trials and from the

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benchmarking of industry which provide context and insight relevant to the research questions that will be useful for industry and policy makers alike.

6.2 Cut off criteria

Cut off criteria provide the specifications on which processes should be included based on their contribution to the overall impact. In this case, processes that are assumed to contribute less than 1% to the overall impact are not included within the assessment. For example, we have not included broodstock management as each brood fish contributes several thousand eggs from which fish several tonnes of harvest weight fish can be produced.

6.3 System Boundary

The system boundary is different from the cut-off criteria. Whereas the cut-off criteria discounts certain processes due to low contribution, the boundary setting is more associated with the function of the system. The boundary of the study defines what data is included and the end point of the study, especially where there are several co-products used in circular economies with multiple reuse and recycling options. In GAIN, for example we are interested in the use of processing by-products in aquafeeds at the farm performance level only. We are not concerned with the use of processing by-products for pet foods and not investigating multiple uses in nutraceuticals or industrial uses such as leather, although there is significant interest in these avenues. Proxies for some of these utilisation pathways can be determined through economic allocation and provides a more accessible analysis than expanding the systems for all the different co-products.

6.4 Allocation

In LCA, a problem arises when more than one product results from a single production process and allocation is the usual method applied to resolve the issue. This problem is referred to as multi-functional co-product allocation and refers to how the impacts from the multi-functional process should be apportioned between the different co-products, e.g. fishmeal and fish oil resulting from the rendering process, or fillets and by-products resulting from the fish processor. In many industrial cases of multifunctional production, it may be possible to subdivide the inputs and emissions between co-products, e.g. different makes of car from a factory. In the case of fish culture and processing, this is not possible because it is impossible to separate the co-products which cannot be produced individually, i.e. it is not possible to produce a fish fillet without producing fish by-products and therefore the inputs to each co-product cannot be subdivided and must be "allocated" according to some logical reasoning. The logical solution seems to be to apportion impacts according to the relative mass of different co-products, but that can often lead to skewed interpretation, when the target product and more valuable part of the production is much smaller in mass than the other co-products. Common examples are in diamond or gold mining where the vast majority of impacts would be apportioned to the rocks instead of the diamonds or gold. This could be considered when evaluating under-utilised fish by-products from a processor. Notable previous LCAs of salmon aquaculture that highlighted marine ingredients derived from fisheries by-products such as Pelletier and Tydmers (2007) and Pelletier *et al.* (2009) used a partitioning procedure based on embodied energy within the

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co-products because they believed that food production is underpinned by biophysical flows which should be the foundation for LCAs of food production. Consequently, fisheries by-products were shown to have a large embodied environmental burden that resulted in salmon production using by-products having much higher impacts than salmon produced with marine ingredients sourced from forage fisheries. The conclusion that can be drawn from Pelletier *et al.* (2007; 2009) is that by-products from fisheries should not be used in aquafeeds and that forage fishery resources are better. The premise for GAIN was that the conclusion and method used by Pelletier *et al.* (2007; 2009) was counterintuitive, because fish cannot be produced without by-products, their embodied burden cannot be avoided by not using them and further impact would most likely result from further sourcing of virgin raw materials, from fisheries, terrestrial or novel ingredient alternatives. Essentially, the methodology only captures a small part of a broader food system and misinterprets the consequences of actions within a small part of the system. In the early days of developing ISO standards and the hierarchy of allocation principles, it was stated that allocation should be applied according to “effect oriented” causality (Ekvall and Finnveden, 2001), specifically that the allocation choice should not lead to reduced recycling in favour of sourcing more virgin materials. However, this underlying principle is often overlooked when applying allocation procedures.

Circular economy principles are the central tenet of the GAIN project. Furthermore, by-product use is encouraged by major 3rd party aquaculture certifiers ASC (2017), GAA (2016) and GlobalGAP (2019). In GAIN, we have favoured a partitioning procedure based on economic value, which allocates impacts to the co-products according to their economic share. The methodology acknowledges the motivation for industrial practices, such as diamond mining, and the transition from waste products to utilisation through gradual steps by identifying more profitable markets, which usually result in more sustainable application. In regard to the application of fisheries and aquaculture by-products, it aligns with the food recovery hierarchy provided by the US EPA and adapted for fish-by-products by Stevens *et al.* (2018), where by-product should be directed to food applications, followed by feed, industrial applications and finally energy recovery and disposal. Hence, the motivations of certifiers, the environment agencies and those promoting circular economy initiatives such as the EU Circular Economy Action Plan (CEAP) (EC, 2015) and has been adopted into the PEFCR for feed (EC, 2016).

An example of economic vs mass allocation can be seen in Table 6.1 which shows allocation factors for the catch composition of Spanish hake fisheries according to Vázquez-Rowe *et al.* (2011) and price data from FAO Fishstat database (FAO, 2020a). The detailed methodology for calculating the LCA of marine ingredients is provided in Deliverable 4.4.

Table 6.1 Mass and economic allocation factors applied to Spanish hake fisheries. (Catch data from Vasquez Rowe et al 2011, price data is ten-year average prices according to FAO (2020a) commodity data

Species	Catch, kg/tonne	Price, $/kg	Price x catch	**Mass allocation %**	**Economic allocation %**
Atlantic Mackerel	210	0.65	135.48	**21.0**	**10.5%**
Blue Whiting,	430	1.03	443.53	**43.0**	**34.4%**
European hake	180	2.89	520.07	**18.0**	**40.3%**
Horse mackerel	180	1.06	191.12	**18.0**	**14.8%**

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Long term price data is used because of the short-term volatility in prices (especially fisheries catches) can lead to skewed outcomes and cloud real changes in environmental performance over time. However, it can be seen from Table 6.1 that European Hake receives the larger share of the allocation, although not the major contributor to the catch volume, but reflecting the motivation of the fishery. Similarly, Norway Lobster only makes up 19.4% of Danish, high-fuel-intensity "Norway lobster fishery" catches according to Thrane (2004) but has 57.7% of the catch value. Economic allocation was applied in the same way throughout the value chain, wherever multi-functional processes occur at mixed fisheries, processing to produce fillets, other products for human consumption and by-products, and at the marine ingredients rendering stage to produce fishmeal and fish oil. Figure 6.2 shows how the embodied impacts (in this case Global Warming Potential) of herring are apportioned at the processing stage to fillets and by-products by mass (red) or economic (green) allocation. The embodied impacts within the by-products are then carried through to the feed and then the final aquaculture product. Understandably, this has a major effect on the outcomes of an LCA study discussed above.

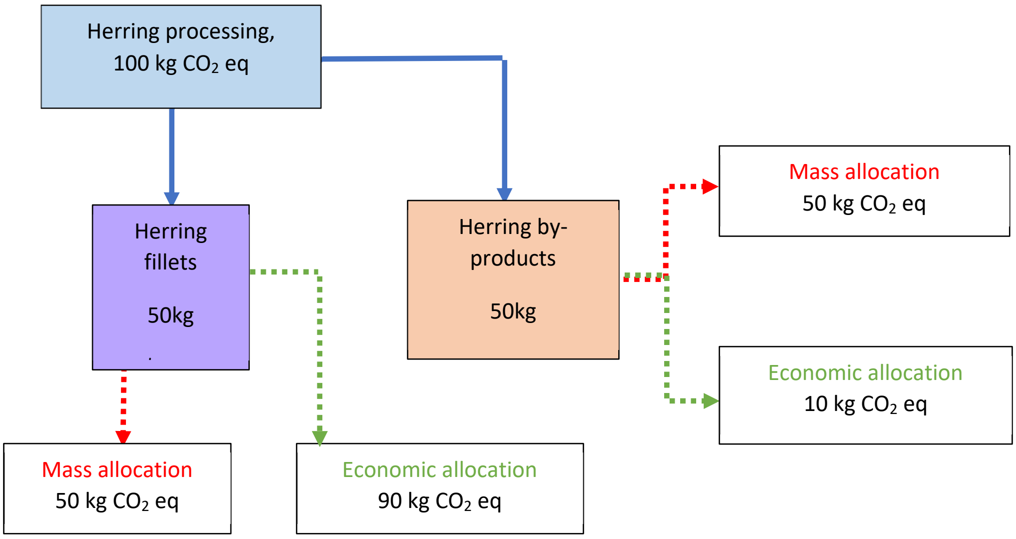

Figure 6.1 Hypothetical example of two different allocation procedures and the effect on LCA results

Other solutions to the co-product allocation dilemma include expanding the boundaries of the system to include the life-cycle of all co-products. While this provides a good overview of production systems, the analysis can become unwieldy and lose sight of the original goals. In the case of food production systems, this is especially the case as there are many co-products involved though-out the feed provision stage, including many from arable crops and is rarely applied although some limited expansion can provide valuable insights in some cases. In this report some limited system expansion is used to show the impact of collective products from processing and how EISI indicators such as EROI and productivity per FTE can be applied.

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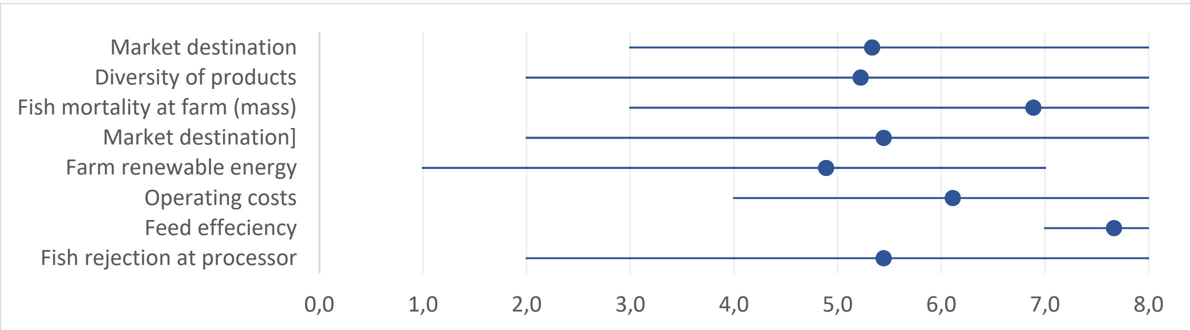
Section 7. Data analysis and EISI construction and interpretation

7.1 Data cleaning and verification

Most relevant secondary data were used for building LCA models. Secondary data particularly related to feed ingredients. While, many established ingredients are well described in the literature or within the LCA databases, a few are not such as guar protein and many of the novel feed ingredients used in the GAIN nutrition trials. The LCIs for these ingredients are given in Annex 1. In many cases, the data are only available from sources that report on lab trials or pilot work and not scaled to commercial levels, and lower efficiency would be expected. Where possible, commercial level data were used to build the models and all data were subject to representativeness testing using the NUSAP pedigree as part of the horizontal averaging process between data sources (Henriksson *et al.*, 2013). A series of literature data sources has three levels of uncertainty (or variability) within it; 1) the inherent uncertainty within a single source 2) the uncertainty between more than one source (spread) and 3) the representativeness of the data of any one source. Therefore, data are weighted according to their uncertainty to produce the final average value that is used for the analysis. Outliers and least relevant datasets were excluded from the modelling if they were orders of magnitude different from the median or if they were from lab or pilot trials when commercial data were also available. Primary data were triangulated for verification purposes when possible and verified against other studies where available.

7.2 Weighting

The EISI indicators were weighted according to stakeholder feedback during the Delphi process of the VCA surveys conducted as part of Task 4.2. Stakeholders were asked to score the different indicators according to how important they regarded them for the industry on a scale of 1 to 8. However, stakeholders tend to regard the indicators from a very local perspective rather than a global supply perspective. Although they understand well that carbon footprint is important within the value chain, this is less evident for issues such as water or land footprints that are important for agricultural feed ingredients.



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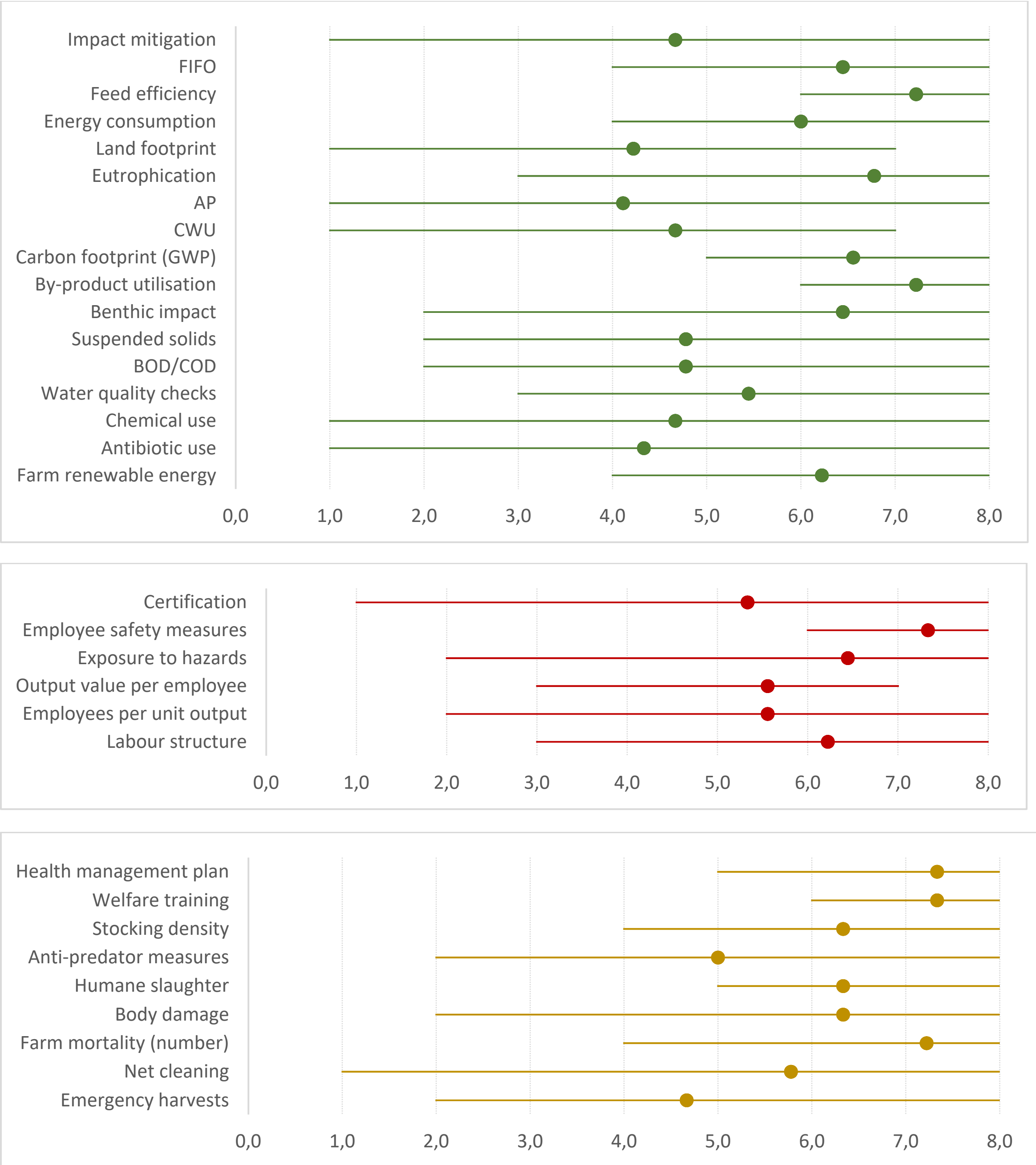

Figure 7.1 Stakeholder scores given to different sustainability indicators a) Economic, b) Environment, c) Social d) Welfare. Dot is the mean and error bars are max and min values.

7.3 Correlation and sensitivity analysis/ aggregation

Changes to farm practice generally have effects on multiple indicators, and thus we expect there to be correlations between indicators, both between farms, and within a single farm if comparing indicators before and after a change in farm practices. The pattern of correlations will be specific to particular industries and their current resource use; as an example, in transport-dependent industries

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there is a strong correlation between total energy consumption and greenhouse gas emissions, but in cattle farming they are decoupled as the animals themselves are the main source of emissions. Thus to understand how different indicators are correlated we must use industry-specific data and models.

In order to assess how LCA and some other EISI indicator changes are correlated when farm practice changes, we used a process of sensitivity to change within an LCA model for Norwegian salmon. That is, factors were modified within the model and how the indicators responded was assessed. The sensitivity assessment was conducted mainly around feed composition as feed contributes to the majority of impacts throughout the value chain. The changes that were made were by changing the composition of the national industry feed mix from the three different companies by 5% in each case (feed company 1 proportion increased by 5% other companies down by 5% collectively) and by replacing the proportion of marine ingredients with soy or rapeseed oil by 5%. The energy provision of farms was changed as well, one at a time, to either all electric or all diesel within the total industry model to see the effect on certain environmental indicators. This process is shown in Figure 7.2

This process resulted in n=53 changes to the sets of indicators values, each representing the effect on the indicators of some change in farm practice. The chosen indicators are those related to environment that were included in the LCA, measurement scales were selected so that low values represent improved environmental performance (e.g. low fraction of non-renewable energy was selected rather than fraction of renewable). We describe the change in indicator values after a change as a 'sensitivity', although this is not a formal sensitivity analysis as it is not possible to translate this to a rate of change relative to a rate of change in a single model parameter. These sensitivities in the indicator values were subjected to two different multi-variate analysis. Firstly, an exploratory analysis of the bivariate correlations between pairs of indicators; secondly, a principal components analysis (PCA).

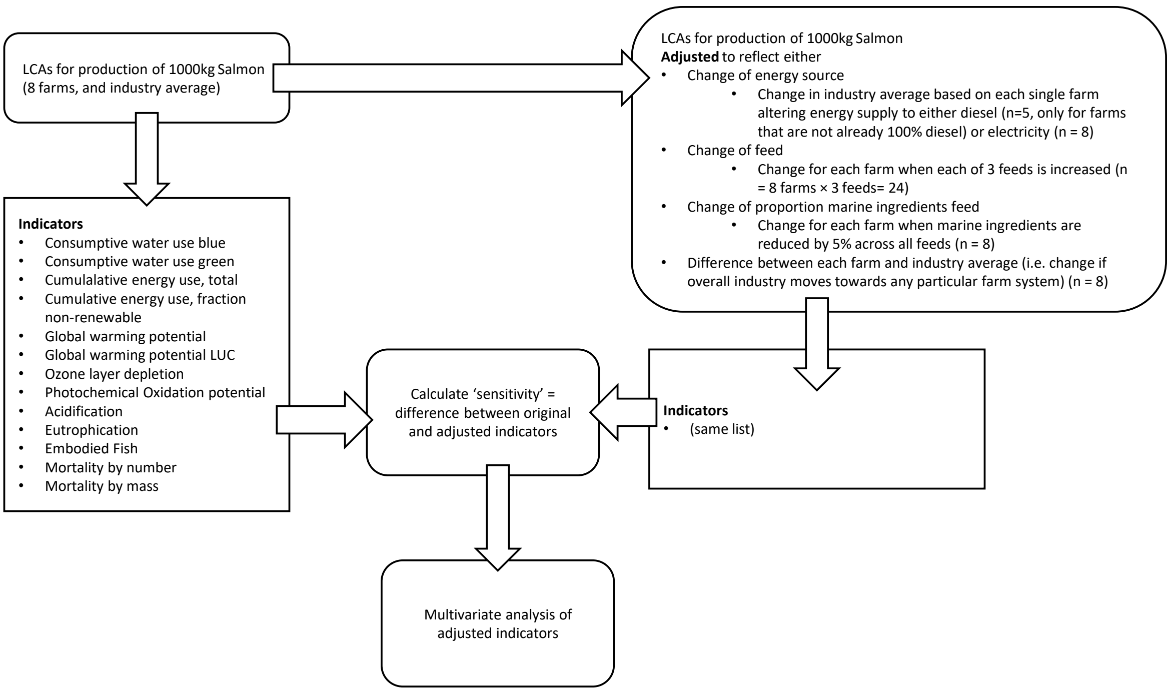

Figure 7.2 Illustration of the process of altering the LCA models and calculating changes in indicator values prior to analysis.

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7.3.1 Bivariate coefficients of correlation

Strong correlations were seen between many pairs of indicators under the changes modelled, as shown in the heatmap in Figure 7.3

Different indicators were correlated for different types of change to farm practice, see Figure 7.4 for examples. It can be seen from Figure 7.4 that there is a clear correlation between acidification and global warming in panel (a), i.e. whatever type of change is made to farm practice in the LCA model, if acidification increases then global warming potential also increases. Panel (b) shows a significantly different pattern for the relationship between blue water use and global warming potential. For the specific farms modelled (purple points and line), there is a positive correlation, i.e. any farm with higher blue water consumption use also has greater global warming potential. When energy source is directly manipulated, however, the relationship becomes inverse, i.e. global warming potential decreases when water use increases. This particular pattern is due to increased water use through hydro-electric generation when farms switch energy from diesel to grid electricity in the models.

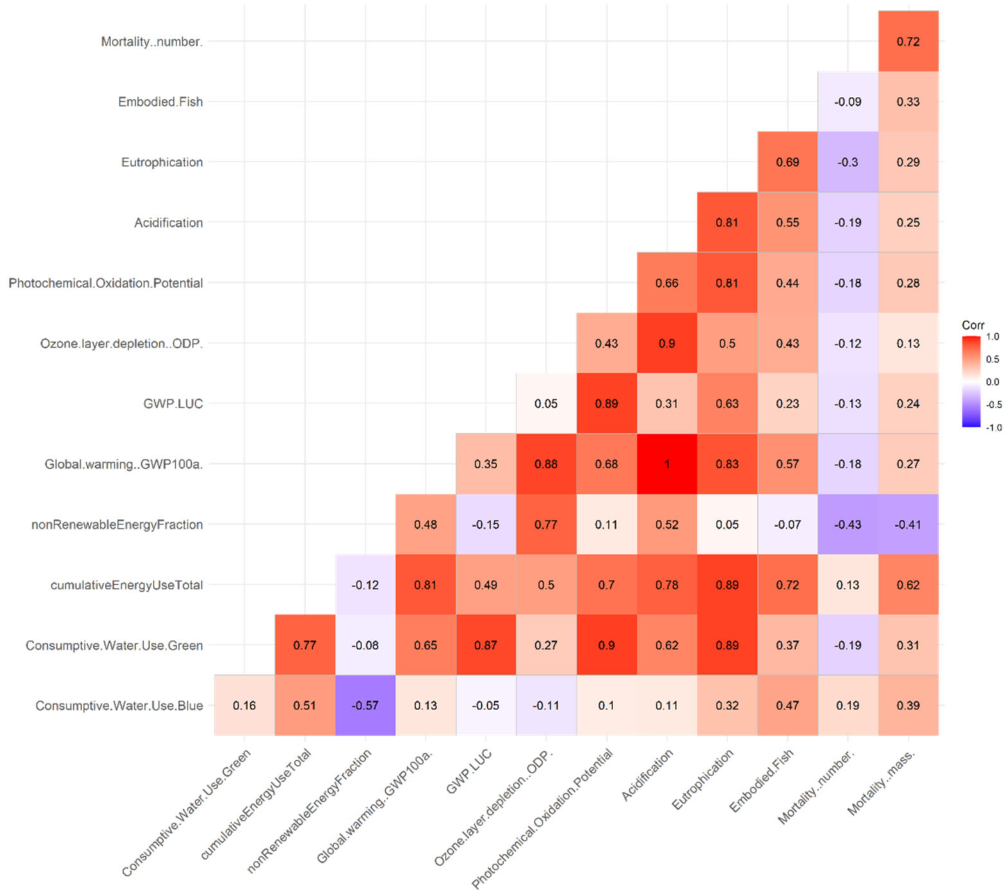

Figure 7.3 Heatmap showing coefficients of correlation (Pearson's R2) between pairs of indicators

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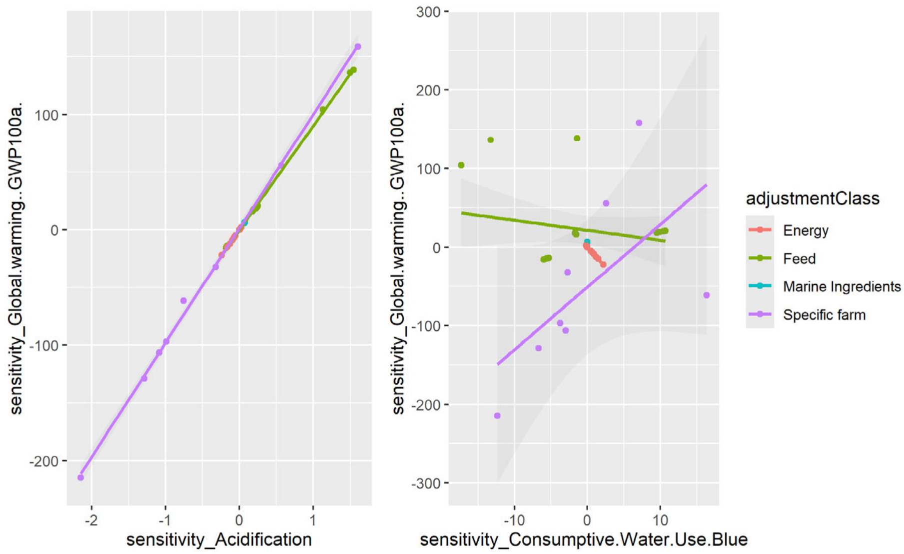

Figure 7.4 Scatterplots of indicators values under different changes to farm practice. Values used are the sensitivities, i.e. the change in the indicator value after making an adjustment to the LCA model. (a) acidification vs. global warming potential (b) blue water use vs. global warming potential. Each point represents the change in the indictor value after making a particular change to an LCA model. Points are coloured according to the type of change that was made (energy, feed, marine ingredients, or specific farm practice compared to industry average).

The coefficients of correlation were used to perform a cluster analysis on the indicators. The resulting hierarchy of clusters is shown in Figure 7.5. This suggests that the two measures of mortality be clustered; blue water use and renewables; ozone depletion, global warming potential and acidification; land use change, green water consumption and oxidation potential; and embodied fish, total energy and eutrophication.

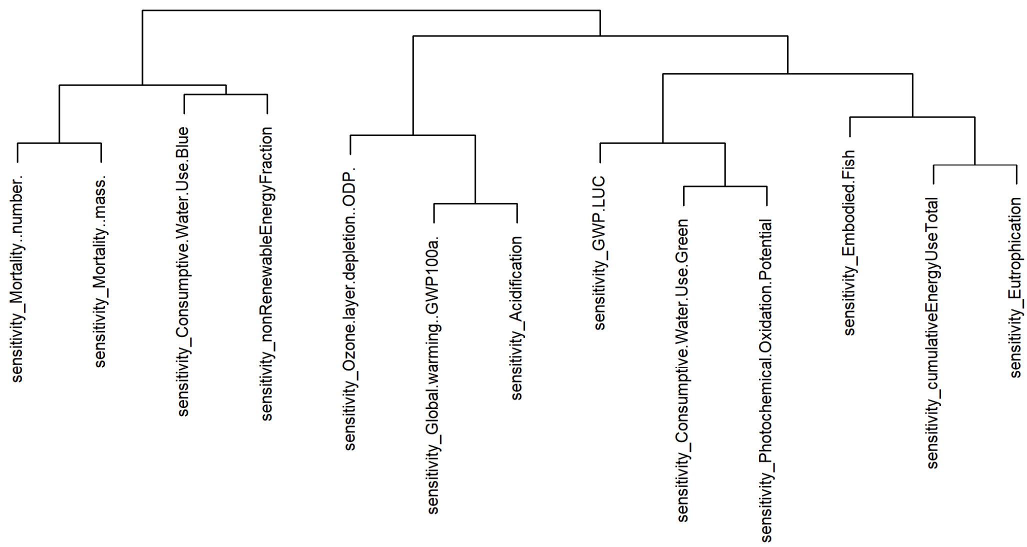

Figure 7.5 Cluster analysis of indicators, based on the sensitivity values described above (i.e. the change in indicator value from the baseline scenario after adjusting the LCA model). Clustering is based on distance calculated from the Pearson coefficients of correlation shown in Figure 7.3. Cluster analysis was performed using the 'hclust' function in R version 3.6.2 (R Core Team 2020).

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7.3.2 Principal Components Analysis

The previous bivariate correlation based analysis indicated possible clusters of indicators, and by looking at the scatterplots it was possible to see how the pattern of correlation differed depending on the type of change made to the farm practices in the model (Figure 7.4). In order to observe correlations across the whole set of indicators at once, a principal components analysis (PCA) was used.

PCA was performed on the sensitivities of the indicators described in Figure 7.2. Data (n=53) consisted of 13 variables. Values for the variables were the sensitivity of the indicator value from the baseline scenario to the adjusted scenario. All values were rescaled to unit variance (i.e. shifted and rescaled so sum of squares = 1) before performing the PCA in order to equally weight the indicators regardless of the magnitude of their values on their own measurement units. PCA was performed using the FactoMineR library version 2.4 in R version 3.6.3 (Lê S, Josse J, Husson F (2008), R Core Team (2020)).

The first 3 components of the PCA explained 85% of the variance. Figure 7.6 shows plots of the points against PCs 1-3.

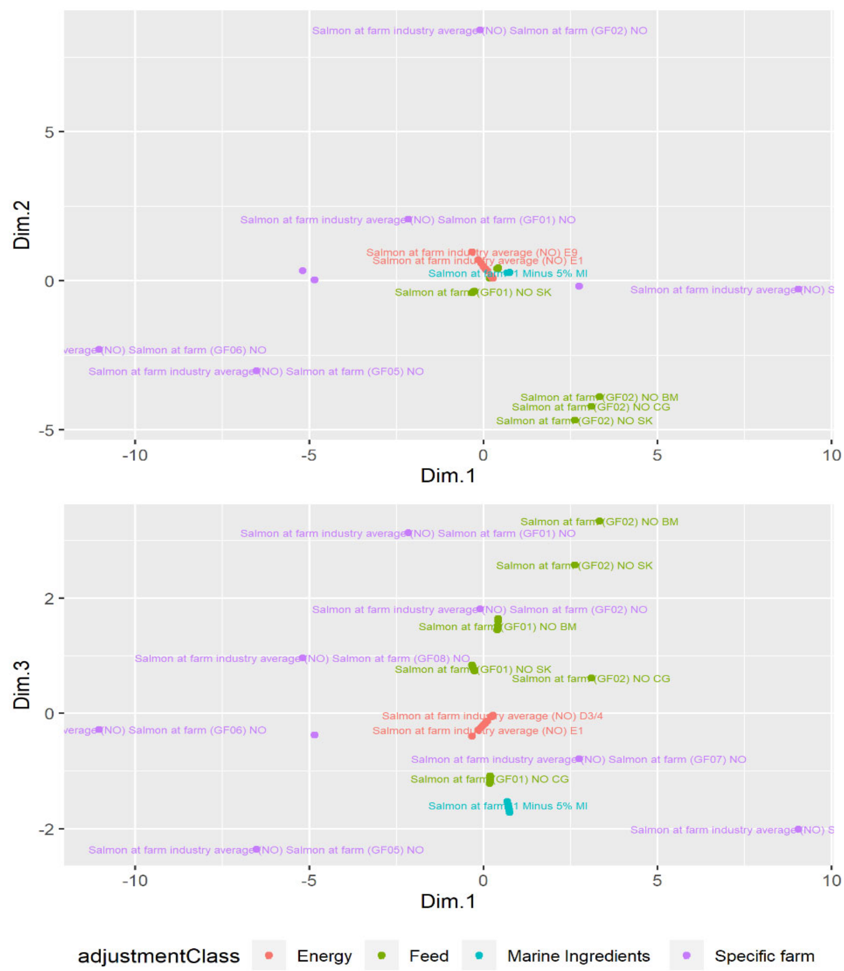

Figure 7.7 Plot of the PCA coordinates for the adjusted LCA models. (a) PC1 and PC2 (b) PC1 and PC3. Points are coloured according to the type of change that was made.

Figure 7.7 shows the weightings of the indicators on principal components 1 and 2, and Table 7.1 shows the numeric weightings for PCs1-3. Note that because sensitivity values have been rescaled to unit variance the weightings in the table indicate the strength with which it influences the principal component value, all measured on the same scale; the values cannot be read as coefficients applied to the raw data values.

Similarities can be observed between indictors with similar PCA weightings, and the clustering in Figure 7.5, for example when looking at GWP, Ozone depletion and acidification.

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Table 7.1 Weightings of each indicator on the first three principal components. For each principal component, the indictors have been sorted from highest (positive) to lowest (negative) weighting. Positive weightings are generally correlated with each other, and negative are inversely correlated with the positive. PCA was performed after normalising the data to unit variance, so these indices should be read as indicating the relative importance of the indicators to overall variance, and not as coefficients to be used on the raw data values.

Indicator	Weighting PC1	Indicator	Weighting PC2	Indicator	Weighting PC3
Eutrophication	0.96	Mortality..mass.	0.67	Mortality..number.	0.48
Global.warming..GWP100a.	0.92	Consumptive.Water.Use.Blue	0.65	Ozone.layer.depletion..ODP.	0.47
cumulativeEnergyUseTotal	0.92	Mortality..number.	0.63	Mortality..mass.	0.37
Acidification	0.90	cumulativeEnergyUseTotal	0.32	Consumptive.Water.Use.Blue	0.27
Photochemical.Oxidation.Potential	0.86	GWP.LUC	0.19	Acidification	0.26
Consumptive.Water.Use.Green	0.85	Embodied.Fish	0.18	Embodied.Fish	0.25
Embodied.Fish	0.68	Consumptive.Water.Use.Green	0.15	Global.warming..GWP100a.	0.24
Ozone.layer.depletion..ODP.	0.67	Eutrophication	0.05	nonRenewableEnergyFraction	0.21
GWP.LUC	0.63	Photochemical.Oxidation.Potential	0.03	cumulativeEnergyUseTotal	0.17
Mortality..mass.	0.40	Global.warming..GWP100a.	-0.28	Eutrophication	-0.15
Consumptive.Water.Use.Blue	0.27	Acidification	-0.32	Photochemical.Oxidation.Potential	-0.39
nonRenewableEnergyFraction	0.18	Ozone.layer.depletion..ODP.	-0.55	Consumptive.Water.Use.Green	-0.46
Mortality..number.	-0.14	nonRenewableEnergyFraction	-0.94	GWP.LUC	-0.68

7.3.3 Conclusions on choice and weighting of indicators to an index

This analysis was intended to inform us about which indicators are closely correlated both between farms and when farms are subjected to changes in practice, and also to suggest whether it is possible to easily summarise overall environmental impact in a single numeric index.

We firstly note that in general environmental indicators are positively correlated (see Figure 7.3). The presence of strong inverse correlations would have implied trade-offs between indicators in the system (i.e. would have shown that improvements in one environmental dimension came at the cost of deterioration of another). With the exception of the mortality measures, the only negative correlation is between blue water use and non-renewable use and this is due to the water requirements of hydro-electric power in Norway. Thus, if blue water use from renewables and mortality are excluded, any weighted sum of the indicators can summarise environmental impact in a number that cannot be gamed by trading off indicators against each other.

The two different measures of mortality were included to capture different aspects of mortality (economic impact of loss of biomass; vs. welfare impact of loss of individuals). The two measures were highly correlated, suggesting that across the industry the pattern of mortality (loss at early vs. late life stage) is similar and either indicator can be used to estimate the other. This correlation was due mostly to existing differences in modelled farms, rather than to the adjustments made to simulate future changes in farming practice; so this pattern may not hold in the future.

The cluster analysis (Figure 7.5) indicated 5 clusters of indicators: the two mortalities; blue water use and non-renewables; ozone, global warming and acidification; land use change, green water and oxidation potential; embodied fish, total energy and eutrophication. The PCA showed though that overall these were not tightly correlated (see Figure 7.7). As the analysis only considered a small set of possible changes to farm practice (feeds, marine ingredients, and energy source) it is possible that

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other changes to farm practice could lead to greater divergence between indicators. The PCA justifies that these indicators do indeed capture different aspects of environmental impact, and supports retaining a wide range of indicators in any index of sustainability.

7.4 Construction of the EISI

The results from the benchmarking exercise were assessed against pre-determined thresholds into a traffic light system over a four scale range of performance; poor, borderline, acceptable and excellent. The boundaries for scaling the performance were based on literature and expert opinion. The weightings for each indicator were then applied when compiling the index. See Section 9 for more detail.

Section 8. Indicator Results

8.1 Salmon industry benchmark

Primary data for the Norwegian salmon industry was collected in the summer of 2019 and included feed formulations from three major international feed manufacturers, farm data from nine farm sites, hatchery data from a “flow through” a Recirculating Aquaculture System (RAS) and RAS/flow-through hybrid, and data from primary and secondary processors to provide a good representational overview of the industry. An aquaculture recycling company that recycled nets, cages etc, was approached but did not wish to participate. Secondary data from peer reviewed literature was used to model feed ingredients along with Global Food Lifecycle Inventory (GFLI) and Ecoinvent data. The LCIs of marine ingredients was included within Deliverable 4.4 and will not be covered in detail here.

8.1.1 Feed formulations

Data on feed formulations is extremely sensitive commercial data and cannot be shown in detail. Tables 8.1 to 8.3 show aggregated formulations for the three major feed companies that supply the majority of salmon feed in Norway, estimated to represent around 90% of the supply based on production levels and reported Feed Conversion Ratios. An industry average feed was modelled based on the quantities of production levels of the companies. The proportion that each feed represents is not provided, so that the aggregated formulation cannot be traced to the company. The formulation for a hatchery feed was also supplied by on of the companies but not presented here.

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Table 8.1 Formulation of grow out feed from Norwegian salmon feed company 1 (NSF1)

Ingredient group		% inclusion
Marine meals	Whole fish (anchovy, blue whiting, capelin etc)	11.1
	By-products (herring, mackerel etc)	1.7
Marine oils	Whole fish (anchoveta, sardine, blue whiting etc)	9.3
	By-products (herring, mackerel, cod etc)	4.7
Vegetable meals and fillers	Soybean protein concentrate, wheat and maize glutens, pea protein etc	49.8
Vegetable oils	Rapeseed, palm oil, coconut oil etc	18.0
Algal oil		0.7
Amino acids	Lysine, methionine etc	1.5
Vitamins, minerals and other additives	Phosphate, pigments etc	3.0

Table 8.2 Formulation of grow out feed from Norwegian salmon feed company 2 (NSF2)

Ingredient group		% inclusion
Marine meals	Whole fish (anchovy, blue whiting, capelin etc)	9.7
	By-products (herring, mackerel etc)	2.7
Marine oils	Whole fish (anchoveta, sardine, blue whiting etc)	8.1
	By-products (herring, mackerel, farmed salmon, etc)	3.6
Vegetable meals and fillers	Soybean protein concentrate, wheat and maize glutens, pea protein etc	52.3
Vegetable oils	Rapeseed, palm oil, camelina etc	20.2
Amino acids, vitamins, minerals and other additives	Phosphate, pigments etc	3.3

Table 8.3 Formulation of grow out feed from Norwegian salmon feed company 3 (NSF3)

Ingredient group		% inclusion
Marine meals	Whole fish (anchovy, blue whiting, capelin etc)	5.2
	By-products (herring, mackerel etc)	1.5
Marine oils	Whole fish (anchoveta, sardine, blue whiting etc)	10.3
	By-products (herring, mackerel, cod etc)	1.1
Fish protein concentrate	By-products (cod, haddock etc)	6.0
Vegetable meals and fillers	Soybean protein concentrate, wheat and maize glutens, pea protein etc	49.6
Vegetable oils	Rapeseed, palm oil, coconut oil etc	19.3
Vitamins, minerals and other additives	Phosphate, pigments etc	7.0

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Table 8.4 Industry average default energy requirement for Norwegian salmon feed milling, per tonne production

Energy type	Electricity, KWh	Heat (gas), MJ	Diesel, MJ
Quantity	85.4	122.6	08.6

8.1.1.1 Life Cycle Impact Assessment of Norwegian salmon feeds.

The results shown represent the principal LCA results that contribute to the overall EISI scoring for the Norwegian salmon benchmark. The full EISI score for the industry is reported in subsection 8.1.2. Figure 8.1 shows GWP, CUE, CWU, LU, BRU, embodied fish, EP, AP for the industry average salmon feed, calculated from the industry primary data reported above.

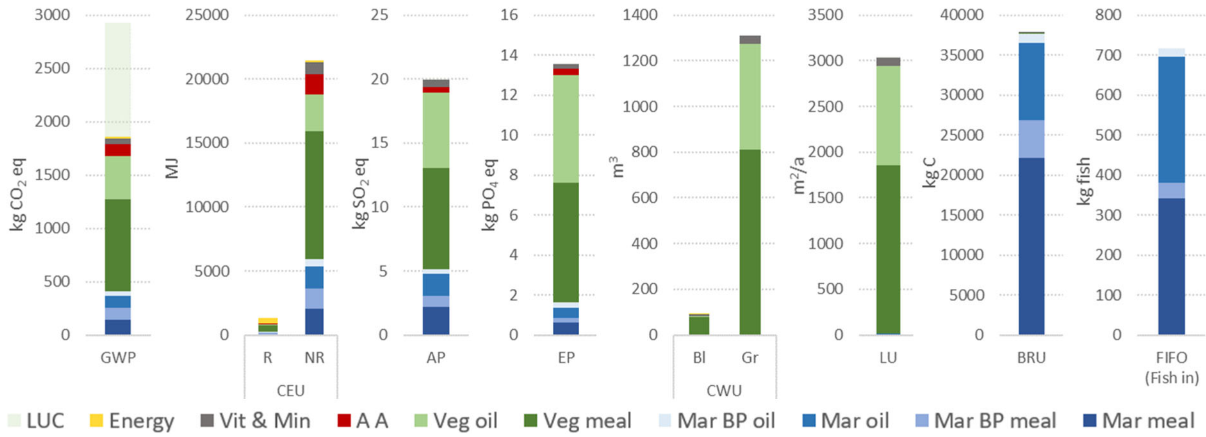

Figure 8.1 Key Life Cycle Assessment indicators for the provisions of 1 tonne of Norwegian salmon grow-out feed (weighted average across three main producers). LUC = Land Use Change, AA = amino acids, BP = by-products, R = renewable, NR = non-renewable, Bl = Blue, Gr = green (water).

The data show that GWP is heavily affected by LUC, which is dominated by the use of soy protein. LUC would be minimal if certified sources were used. However, those data were not provided. Certification agencies stipulate a minimum level of certified soy be used and those farms that are certified need to demonstrate that their feed is responsibly sourced. All farms surveyed for the EISI were certified by at least one of the main certifying bodies. The data shows a continued reliance on non-renewable energy, although much of this is scope 3 emissions due to the energy mix of the producing country of different feed ingredients, therefore outside the control of feed producers. Only a small proportion of the energy used is at the feed mill itself. BRU, largely tracks the embodied fish in marine ingredients although there are some differences related to by-product use as some by-products are sourced from the processing of higher trophic fish species. Conversely, land use and water use are almost entirely from the provision of vegetable proteins and oils with most water use being from rain (green) rather than irrigated (blue). D4.4 demonstrated the trade-off between BRU mostly from marine ingredients and other impacts mostly from vegetable ingredients. Therefore, increased substitution of marine ingredients with terrestrial vegetable-based ingredients is likely to increase all impacts except for BRU and eFIFO which it tracks.

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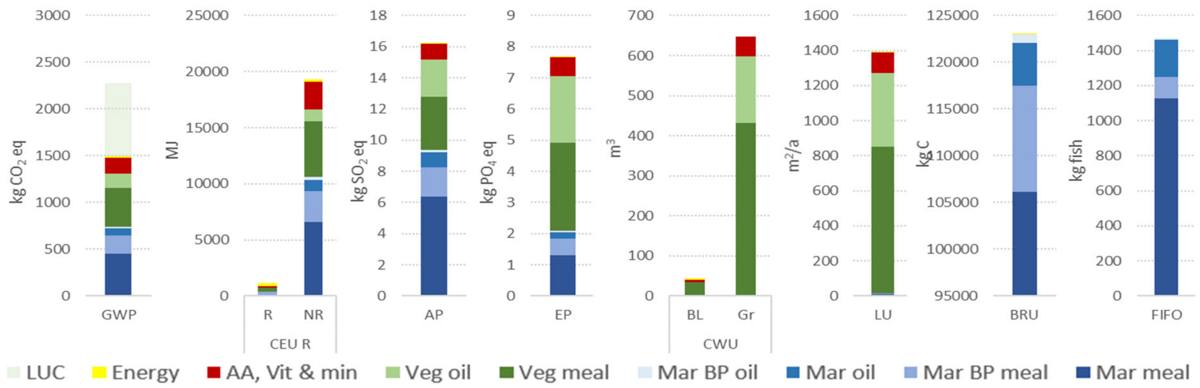

Figure 8.2 Key Life Cycle Assessment indicators for the provisions of 1 tonne of Norwegian salmon hatchery feed (one producer). LUC = Land Use Change, AA = amino acids, BP = by-products, R = renewable, NR = non-renewable, Bl = Blue, Gr = green (water).

The hatchery diet impacts reflect the higher inclusion of marine ingredients with around double the embodied fish and triple the BRU but around half the land use and water consumption for 1 tonne of feed production. Other impacts are also lower apart from ODP. This reflects that marine ingredients are actually very efficient to produce, despite being in critically short supply. Section 8.3 assesses the trade-offs in impacts between different feed ingredients included within GAIN nutrition trials.

8.1.2 Norwegian salmon production

The LCI data from three hatcheries (Table 8.5) and nine grow-out farms (Table 8.6) is presented. Hatcheries produced smolts in a range of sizes, flow through and hybrid RAS producing from 150g to 200g and the full RAS hatchery producing larger smolts to 400g. However, all grow out farms reported stocking smolts at between 65g and 200g. Therefore, the 100% RAS system did not feature in the average industry production to market size and most were deemed to come from the 90% RAS/ 10% flow-through hybrid.

Table 8.5 Life Cycle Inventory of Norwegian salmon smolt production (one thousand smolts) at hatchery gate

	Flow through	**90% RAS**	**100% RAS**
Average smolt size	200g	150g	400g
INPUTS			
Hatchery feed, kg	202.5	165.0	440
Electricity, KWh	848.3	1638	2552
Oxygen, kg	79.0	58.5	160
FTE (male) /yr	0.00158	0.00148	0.00135
FTE (female) /yr	0.000792	0.000986	0.000897
EMISSIONS			
Total nitrogen, kg	8.7	1.03	0.94
Total phosphorous, kg	2.0	0.237	0.21
Total carbon, kg	18.6	2.20	2.02
Mortality, number	115	220	220

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Grow out data came from three companies across nine grow out sites. One site (GF3) grew salmon to around 1.5kg before splitting the stock between that site and another (GF4). For the purposes of modelling, these two sites were treated as one system. Chemical use data were not provided by all farms, so an average was calculated from sites that did provide those data and applied as a default to farms where it was absent. The number of smolts were adjusted according to the initial stocking size declared by the grow out company, compared to the average size of smolts produced by the hatchery. Hatcheries were not able to estimate the mass of mortality as this was generally not measured. Most mortality in hatcheries occurs up to the time when fish are beginning to feed due to deformity, weak fish and those that do not wean on to feed readily. At this stage, they are a fraction of a gramme. Employment was given as an average across companies as labour is shared between sites within the same company.

Table 8.6 Life Cycle Inventory of Norwegian salmon grow out farms used to produce the industry average benchmark, per 1 tonne of salmon live at farm gate

	GF1	GF2	GF3/4	GF5	GF6	GF7	GF8	GF9*
INPUT								
Salmon smolts (90% RAS)*, pieces	167	240	129	95.5	82.5	149	155	255
Salmon grow out feed ind. mix, kg	1239	1274	1240	1238	1188	1306	1228	1341
Diesel use (barge and boat), MJ	1528	1495	775.5	717.5	884.4	1137.3	1065	995
Electricity from grid, KWh	-	-	64.7	7.85	0.36	-	28.0	14.4
Formic acid, kg	1.43	1.719	1.55	1.57	1.57	1.57	1.57	1.57
Anaesthetic*, kg	0.0372	0.0454	0.0409	0.0412	0.412	0.412	0.412	0.0412
Lubricating oil, kg	0.0413	0.0505	0.0455	0.0458	0.458	0.458	0.458	0.0457
Sodium hypochlorite, kg	0.0723	0.0883	0.0795	0.0801	0.0801	0.0801	0.0801	0.0801
FTE (male) /yr	0.00303	0.00303	0.00059	0.00132	0.00132	0.00132	0.00132	0.00202
FTE (female) /yr	0.00088	0.00088	0.00017	0.00033	0.00033	0.00033	0.00033	0.00021
EMISSIONS								
Total nitrogen, kg	53.2	54.7	53.3	53.2	51.0	56.1	52.7	57.6
Total phosphorous, kg	12.3	12.6	12.3	12.3	11.8	12.9	12.2	13.3
Total carbon, kg	114	117	114	114	109	119	112	123
Mortality, number	154	156	67.2	29.0	68.4	70.4	124	10.2
Mortality, kg	57.3	68.8	34.9	7.47	23.0	31.1	28.6	40

* All smolts came from the 90% RAS facility apart from GF9 which came from the 100% flow through hatchery. Anaesthetic was modelled as "benzoic-compound".

Figure 8.3 Shows key LCA trade-offs between the hatcheries, demonstrating how increased energy consumption at the local level is offset by reduced nutrient emissions in RAS systems. Although there is an increase in energy use, the rise in GWP is not large because a lot of the local energy supply is from renewables and the overall GWP is still dominated by the provision of feed rather than the use of electricity at the hatchery. LUC is also from feed provision rather than locally. The data in Figure 8.3 has been adjusted for the size of smolt whereas the data in Table 8.5 is per 1000 smolts for each hatchery. The overall water use was not available although all hatcheries claimed that the water abstracted was returned to the watercourse so that there was in effect, no water consumption. However, it is likely that there would be minor water loss due to evaporation and splash.

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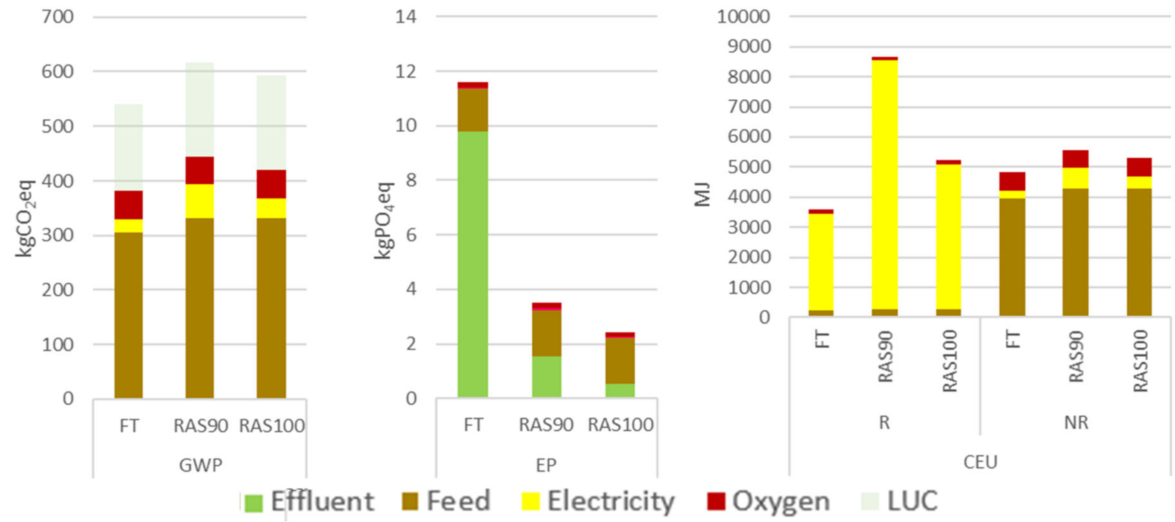

Figure 8.3 Global Warming Potential, Eutrophication Potential and Cumulative Energy Use (R = renewable, NR = non-renewable) from three Norwegian hatcheries, adjusted for smolt size per 1000 smolts (200g) at Flow Through (FT), 1333 smolts (150g) at RAS90 and 500 smolts (400g) at RAS100.

Figure 8.4 shows some selected impact category data from the benchmarking of Norwegian salmon farms. The GWP, excluding LUC was 2523kgCO_2eq per tonne of salmon at the farm gate, which is comparable to previous studies for farmed salmon. LUC is contentious to include because the data are calculated within LCA software from default national or regional values for that product, in this case mostly soybean from Brazil. However, in many cases, production is certified, meaning at least 50% of soy must be from responsible supplies guaranteed to have no LUC in the case of BAP (2020), from illegally deforested areas in the case of GlobalGAP (2021) or must have a responsible sourcing plan with low risk of deforestation in the case of ASC (2021). Feed dominated most impact categories apart from Eutrophication Potential which was mostly through effluent at the grow out farm (from the fish excreta). Economic Fish In: Fish Out ratio was calculated to be 0.96 (956kg of embodied fish per tonne of salmon produced), showing that Norwegian salmon production is a net producer of fish. According to Aas *et al.* (2019), the energy content of whole salmon is 12700MJ/tonne, giving an EROI of 0.308 for combined co-products at the processor (0.394 to farm gate), which is somewhat higher than e.g. Pelletier and Tyedmers (2007) who only reported on the edible yield. Mortality numbers were proportionately more at the hatchery than at grow-out due to the larger mortality of small fish in the early stages of production. Employment was also proportionately higher at the hatchery compared to grow-out with 78.7% male employment through the industry. No figures on employment through feed production or other upstream stages were obtained and employment refers only to fish production stages. However, there is a stark difference in the energy mix compared to the hatchery stage, with much more non-renewable energy related to feed as the hatchery stage is only a small contributor to the energy consumption overall.

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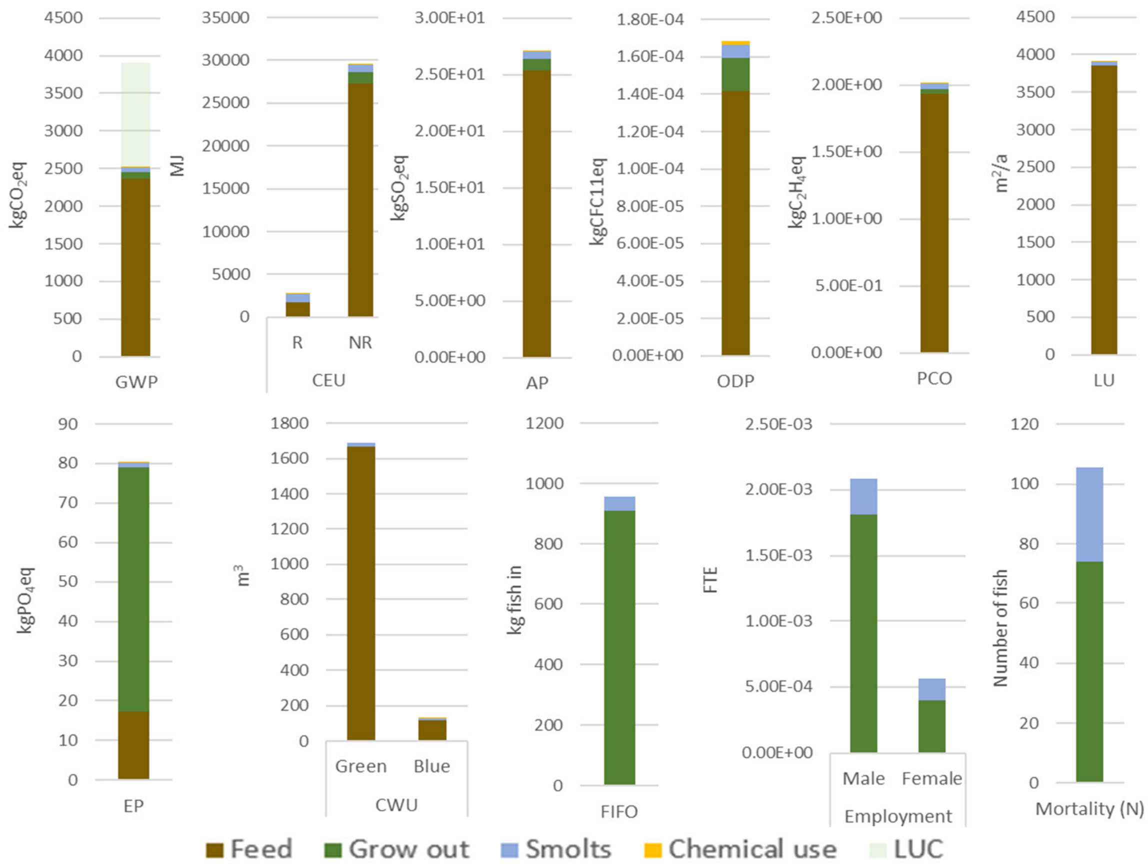

Figure 8.4 Selected sustainability indicators from LCA of Norwegian salmon benchmark data. One tonne of salmon at farm gate.

8.1.3 Salmon Processing

Salmon processing data was collected from a primary and secondary processor. Both were fairly small scale, processing 23000 tonnes and just under 2000 tonnes respectively, although they also stated intentions to expand in the future. The Life cycle inventory for the plants is shown in Table 8.7. No data was provided on wastewater quality, which in some cases can be high in eutrophying compounds, BOD and suspended solids depending on the treatment used. Secondary processing was the only part of the value chain in which female employment was more than male employment and contributes significantly to the overall employment of the sector. However, much of Norwegian salmon is exported as HOG (D2.7, D3.3) before it can be further processed. Secondary processing produced mainly frozen fillets for human consumption, but a large amount of the co-products were exported for human consumption also, including head and tails, with much of the frames, trimmings and bellies sold for pet food and feed applications.

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Table 8.7 Life cycle Inventories of Norwegian salmon primary and secondary processing facilities

	Primary		Secondary	
INPUTS				
Salmon, kg	1000 (live)		1000 (HOG)	
Electricity, kWh	133		1546	
Polystyrene boxes, kg	24.9		-	
Water, m^3	2.8		53.42	
Male FTE	0.0012		0.00511	
Female FTE	0.0008		0.00769	
OUTPUTS		**Allocation %**		**Allocation %**
Head-on-gutted salmon (HOG), kg	820	99.2		
Viscera, kg	180	0.8		
Fillet (fresh)			6.1	1.2
Fillet (frozen)			486	92.0
Heads			173	1.6
Belly flaps			83.8	1.9
Tails			21.5	1.6
Trimmings			31.7	0.24
Frames			187.6	1.4

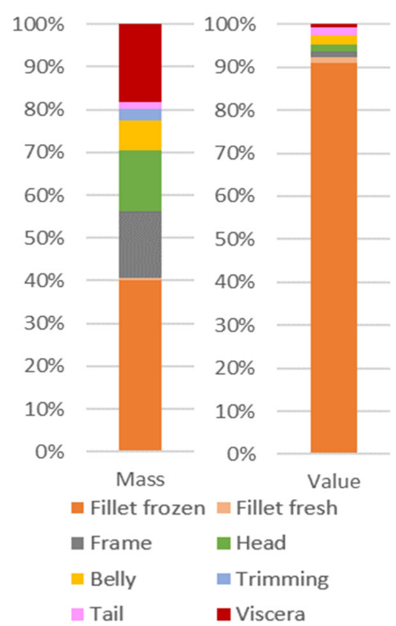

Figure 8.5 Proportion of different Norwegian salmon processing co-products by mass and value

The application of the different co-products is reflected in their value with 93% of the value attributed to fillets and proportionately larger value attributed to heads and tails compared to the remaining co-products. For the purposes of modelling, this results in a larger proportion of the impacts being applied to those co-products because of economic allocation.

Selected impact assessment indicators from the LCA analysis are shown in Figure 8.6. In most cases, the impacts are totally dominated by the salmon raw material input (including LUC) with few added impacts at the processor. There is a fairly large energy consumption, particularly at the secondary processor, but this is mainly from renewable energy, owing to the Norwegian market mix and therefore contributes only a minor amount to GWP. However, packaging disproportionately contributes to Photochemical Oxidation Potential due to the use of polystyrene foam boxes.

The labour mix is interesting in that the processing sector has a large amount of female employees which redresses the gender balance over the value chain, where production is dominated by male employees.

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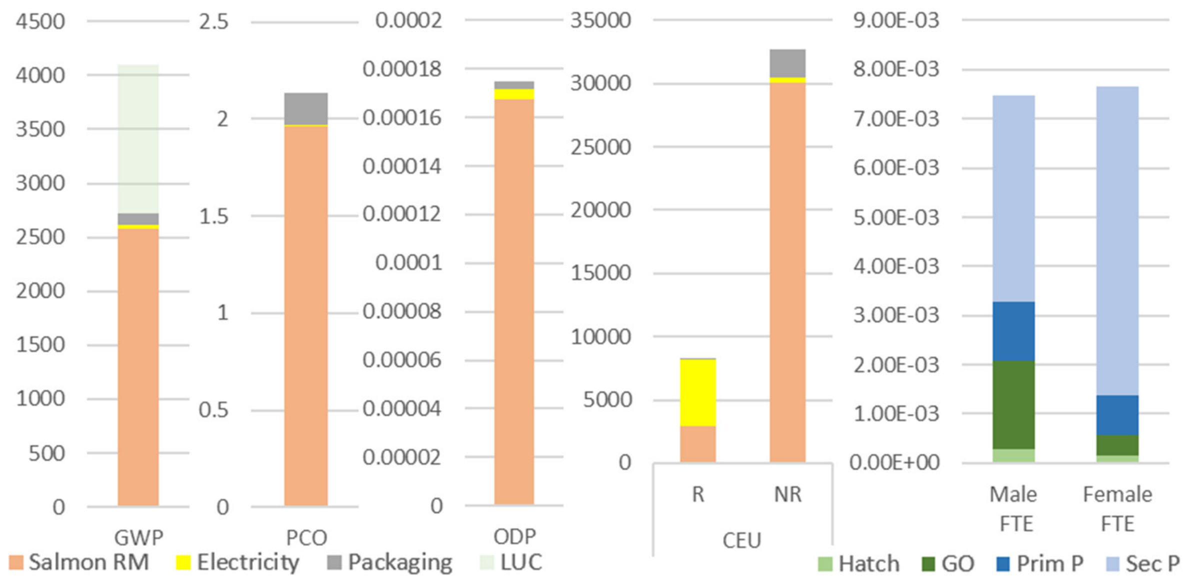

Figure 8.6 Selected Life Cycle Assessment indicators for the processing of Norwegian salmon, per tonne of salmon raw material (RM) processed and break down of male and female full-time employment (FTE) equivalents throughout the value chain (GO = grow out, Prim P and Sec P = Primary and Secondary processing respectively).

8.1.4 Other sustainability indicators for the production of Norwegian salmon

This section provides data collected on other sustainability indicators that could not be measured using LCA. It includes checklist data, scored data and other data that refer to only certain parts of the value chain, such as benthic impact at the farm or processor quality assurance. Table 8.8 shows the scoring of the indicators for which data could be collected. Some economic data were particularly difficult to collect due to their sensitivity.

The data included within Table 8.8 were not tested for correlation as described in Section7.3 because they are mostly qualitative indicators or distinct in their calculation. The exception is EROI which is directly linked to Cumulative Energy Use but not correlated with the ratio between renewable and non-renewable energy. Therefore, all of the data included in Table 8.8 are included in the EISI.

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Table 8.8 Weighted averages of scores for EISI indicators across Norwegian salmon hatcheries, grow-out farms and processors

	Type of indicator	Hatchery	Grow out	Processor	Overall
Record keeping	Ranked score	77.7	60.5	-	62.4
Quantity to human consumption, %	Calculation	-	-	63.1	63.1
Impact mitigation measures	Number	-	-	2.92	2.92
Benthic impact, $g/m^2/yr$	Calculation	-	1098	-	1098
Energy return on investment (EROI)*	Calculation	-	0.394	0.308	0.308
Fish rejection at the processor, % accepted	Percentage	-	-	92	92
eFeed Conversion Ratio	Calculation		1.22	-	1.22
Mortality, mass, kg/tonne	Calculation		38.1	-	38.1
Export market, %	Percentage	-	-	80.6	80.6
Product diversity	Number	-	-	11	11
Gender balance, female:male	Ratio	0.61	0.27	1.44	1.03
Production per FTE, tonnes	Calculation	424*	433	80.1	66.2
Employee safety risk assessment	Check	100	100	100	100
Certification, % of farms certified*	Calculation	100	100	100	100
Emergency harvest, % of production	Calculation	0	2.78	-	2.48
Active body damage, frequency checklist*	Scored %	-	18.5	-	18.5
Staff welfare training, %	Calculation	25	88	-	81.0
Predation measures, %	Calculation	100	100	-	100
Stocking density, kg/m^3 estimated average	Calculation	-	6.34	-	6.34
Humane slaughter	Check	-	-	100	100

*EROI is linked to total production of all co-products at the processor. Production per FTE for hatcheries is per thousand smolts. All farms and hatcheries had GlobalGAP and/or ASC certification. Processors had BRC and IFS certification. Active body damage check is over 6 criteria, checked daily to achieve 100%.

8.2 Polish Carp Industry Benchmark

Data from the Polish carp industry was collected from February 2020 onwards. Unfortunately, the field visit that was scheduled for 3 months was cut short after around a month because of COVID travel restrictions. Although every effort was made to continue data collection remotely, through strong

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partnerships between UoS, ZUT and their network, the data is less complete and representative than for the Norwegian salmon industry. Data was collected from one formulated feed manufacturer and three farms. Polish carp production is typified by much more extensive production systems than most of European aquaculture, with stocking densities limited to 1.5 tonnes per hectare, sometimes with little or no feed inputs. Many farms use some formulated feed, supplemented with grains such as triticale. The processing sector is not well established in Poland with the vast majority of sales being live fish for the Christmas market. However, scenarios on carp processing were investigated as part of the VCA work which is reported in Deliverable D4.2.

8.2.1 Carp formulated feed production

Data from one carp feed mill was collected, aggregated data for which is presented in Table 8.9. There are low inclusions of marine ingredients, but vegetable protein ingredients include soybean and sunflower protein concentrates and to a lesser extent, DDGS and rapeseed meal. There were no vegetable oil ingredients with lipids coming from fish by-product oil and that included within the other vegetable ingredients.

Table 8.9 Formulation of grow out feed from Polish carp feed factory

Ingredient group		% inclusion
Marine meals	Whole fish (anchovy, blue whiting, capelin etc)	3.0
Marine oils	By-products (herring, mackerel, cod etc)	4.0
Vegetable meals and fillers	Soybean protein concentrate, sunflower, rapeseed, triticale etc	84.0
PAPs	Blood meal	4.0
Vitamins, minerals and other additives	Phosphate, pigments etc	4.0

Selected impacts categories for one tonne of carp feed production are presented in Figure 8.7. The impacts from Polish carp feeds are generally well below those of salmon feeds as they rely on much less energy intensive ingredients, including unprocessed grains and meals compared to large quantities of soy protein concentrate, wheat and maize glutens, and rapeseed oil. Low quantities of marine ingredients lead to lower BRU and embodied fish compared to salmon feeds.

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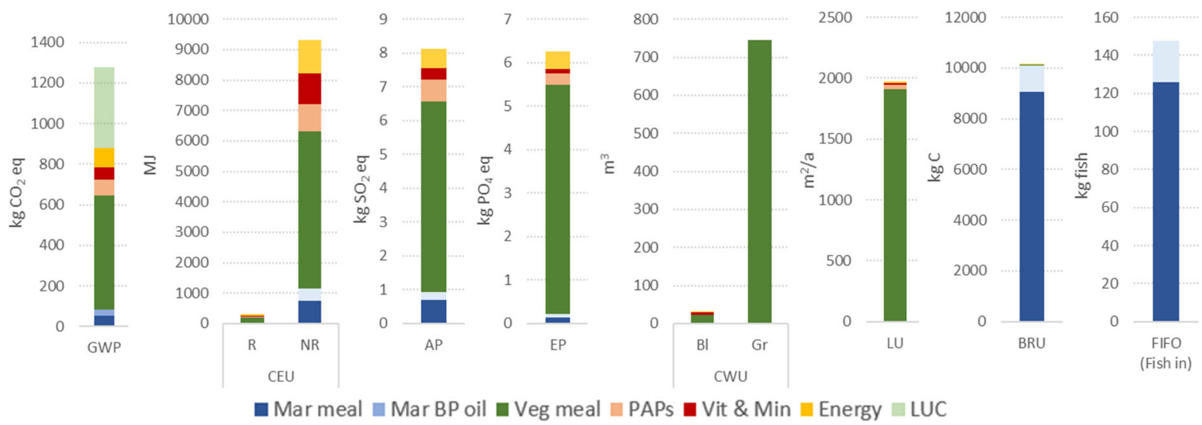

Figure 8.7 Contribution to selected impact categories for production of 1 tonne of Polish carp feed.

The life cycle inventories of the three Polish carp farms are given in Table 8.10. The input data provided were only complete for one farm including fuel and chemical use data. Where data were missing, they were assumed to be the same between all farms.

Table 8.10 Life cycle inventory for three Polish carp farms per tonne of production.

	Farm1	Farm2	Farm3
Culture area, ha	21.7	13.6	57.5
INPUTS	-	65	-
Carp fingerlings, kg			
Triticale, kg	5636	-	-
Formulated feed, kg	-	2400	-
Diesel, MJ	2387	2387	2387
Calcium chloride, kg	36	36	36
Copper sulphate, kg	3.6	3.6	3.6
Calcium hydroxide, kg	145	145	145
Lime, kg	1818	1818	1818
Sodium chloride, kg	36	36	36
FTE (male) /yr	0.108	0.8	0.777
EMISSIONS			
Total nitrogen, kg	8.7	1.03	0.94
Total phosphorous, kg	2.0	0.237	0.21
Total carbon, kg	18.6	2.20	2.02
Mortality, number	1087	8418	75619
Mortality, kg	138	323	2017

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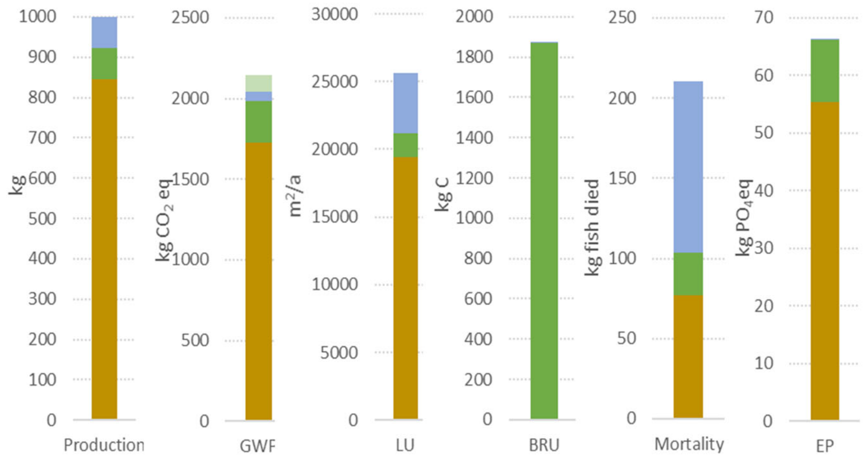

Figure 8.8 Contribution to selected LCA impact categories from three Polish carp farms, weighted to 1 tonne of total production.

There was considerable variability between the farms in that one farm fed only triticale grain, another used formulated feed and the last only natural feeding. There was a considerable difference in the number of mortalities between the different farms with the most extensive farm having a much higher number and biomass of mortality compared to the most intensive farm. Farm 3 reported mortality as high as 70% over the first year of production then a further 50% over winter and in subsequent years, compared to Farm 1 that had 30% in the first year followed by 20% in subsequent years. The vast majority of mortality was from predation, which is difficult to control over such large production areas. There was also considerable economy of scale between the farms with the farm with the highest production having far fewer FTE per unit production. Farm 1 and 3 produced their own fry, some of which were sold by Farm1, where as Farm 2 bought in fingerlings from outside.

The variability between production sites was much larger than for salmon, highlighted by the different contributions to selected impact categories in Figure 8.8. Farm 1 was the largest, producing around ten times the quantity of both the others. Farm 2 was the only one using formulated feed with marine ingredient inclusions, so made up nearly all of the BRU and a slightly disproportionate contribution to GWP. Farm 3 was much larger despite having quite low production so contributed disproportionately to land use, and its extensive nature made it much more susceptible to predation than the more intensive farms as described above.

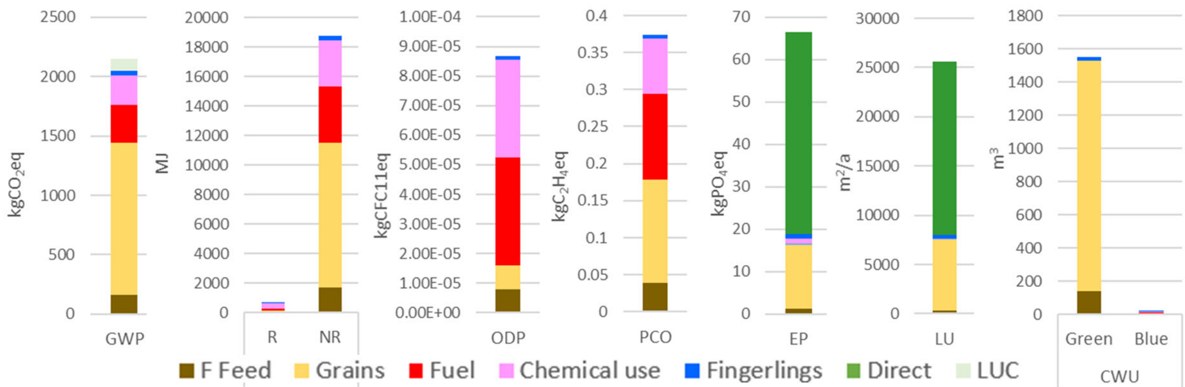

Figure 8.9 Contribution to selected LCA impact categories of Polish carp production (three farms). F Feed = formulated feed.

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Table 8.11 Weighted averages of scores for EISI indicators across Polish carp farms

	Type of indicator	Grow out
Record keeping	Ranked score	1.72
Energy return on investment (EROI)*	Calculation	1.09
eFeed Conversion Ratio	Calculation	4.95
Mortality, mass, kg/tonne	Calculation	211
Export market, %	Percentage	7
Product diversity	Number	1
Gender balance, female:male	Ratio	0
Production per FTE, tonnes	Calculation	5.45
Employee safety risk assessment	Check	0
Certification, % of farms certified*	Calculation	0
Emergency harvest, % of production	Calculation	0
Active body damage, frequency checklist*	Scored %	0.26
Staff welfare training, %	Calculation	84.6
Predation measures, %	Calculation	100
Stocking density, t/ha estimated average	Calculation	2.54
Humane slaughter	Check	7.69

Figure 8.9 shows the contribution to selected LCA impacts according to different inputs for one tonne of carp production. Most of the contribution to GWP and CEU were from feed, either formulated or grains, similarly to salmon production. However, the contributions from fuel use and chemical application were considerable and were the major contribution to ozone depletion potential (ODP), particularly calcium hydroxide and lime application. Direct land use at the farm was also larger than for feed production, due to its extensive nature, which sets carp production apart from salmon and other intensively produced finfish.

According to Chakraborty *et al.* (1995), the energy content of whole common carp is around 21000MJ/tonne giving an impressive EROI of 1.09 for the unprocessed product at the farm gate, despite high FCR and mortality. The FCR for carp production is high compared to other aquaculture species at 4.95, averaged between the sites assessed. However, the largest contributor is from unprocessed triticale grain with the non-fed and formulated fed systems, only contributing to about 15% of production.

The employment gender ratio female to male was zero as employment was completely made up of male employees. On average, 0.183 FTE were required to produce a tonne of carp, making the productivity only 5.45 tonnes per employee, considerably lower than in the salmon industry, but equating to around 3400 FTE to produce the around 18500 tonnes according to FAO Fishstat (FAO 2020a).

8.3 UK Shellfish Industry Benchmark

The majority of the bivalve producers in Scotland form part of a co-operative. The co-operative has one main processing facility in central Scotland where all bivalves produced from its members can be processed and sold to UK retail and food service. The co-operative also owns a smaller processing facility in Shetland which processes some of Shetland’s bivalves for food service. This value chain in Scotland is different to other areas of the UK where the majority of bivalve products are exported to EU countries as either full-grown or half-grown bivalves for further processing or rearing. The farm

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uses suspended long lines to grow mussels until the reach market size of roughly 13g which takes around 3 years. Mussel spat is collected either through natural settlement onto the long lines or through natural settlement in specific nursery areas designated by the farm. The latter system has been put in place due to low spat yields on certain sites. This culture method compares to the rest of the UK and some EU production (Tamburini *et al.*, 2020). Although other culture methods do exist, for example in Wales the majority of mussels are produced through bottom laid culture, where seed is dredged and then placed in bottom culture sites to grow mussels. Although traditionally sites are located less than a few miles from the shoreline, in the South of England the first offshore mussel farm in the UK has begun producing mussels 3-6 miles offshore in higher energy waters. Elsewhere in Europe mussel are also produced through raft culture systems (Iribarren *et al.*, 2010; Ziegler *et al.*, 2012), and in France traditional mussel farming uses Bouchots (Aubin *et al.*, 2017).

Oysters are grown the intertidal zone inside bags on trestles for between 2.5-3 years until market size (~70g). This culture method is used elsewhere in the UK and across some areas of the EU. However, mussel can also be produced by suspended long line systems, similar to that of mussel culture (Tamburini *et al.*, 2020). Oyster seed is purchased from either of the two hatcheries in the UK and laid into trestle bags at the start of the production cycle.

Market size bivalves from these farms are sent to the processing factory via lorry transport and include a ferry journey from Shetland. The percentage of products produced by the processing site and that were assessed in this study include: live oysters (1.7%), live mussels (4.6%), plain cooked mussels (26.8%) and cooked mussels in a sauce (66.9%). Live mussels are sent from farms and over 95% of these mussels are sold as cooked products. Depuration depends on the quality or “class” of the water in which they are grown and as most mussel farms in Scotland are from Class A waters, these products do not require to be depurated. If mussels from Class B waters are harvested, these bivalves are used for cooked products only, as the pasteurisation cooking method eliminates the need to depurate these mussels. Oysters are also sent to the processing facility via lorry transport and around 53% of oysters annually are depurated prior to processing and packaging as live oysters.

Table 8.12 Life Cycle Inventory data for modelling of UK shellfish production, from Fry et al (2012) except primary data on employment from a Scottish mussel and an oyster farm.

	Mussels	Oysters
INPUTS		
Polypropylene rope, kg	13	
HDPE buoys, kg	4.4	
HDPE pegs, kg	3.5	
HDPE mesh bags, kg	2.3	10
Nylon ties, kg		7.6
Steel trestles, kg		71
Electricity, kWh	46	716
Diesel, MJ,	1052	1803
Lubricating oil, kg	0.94	1.6
FTE (male) /yr	0.011	0.286
FTE (female) /yr	0.00069	0.0952
MISSIONS		
Losses, kg	138	20

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Table 8.12 shows the LCI data for mussels and oysters taken from Fry et al (2012). Data for UK shellfish industry was collected from a combined mussel and oyster processing plant that represented over 80% of the Scottish shellfish industry. Although producers were approached in Scotland, Northern Ireland and England, none were able to supply the necessary data in the GAIN timeframe, largely due to continuing COVID restrictions although some data regarding employment was recorded in time. LCI data on mussel and oyster production was taken from the SARF078 report Fry (2012), which provides the most representative information on typical UK shellfish systems, apart from employment data.

Figure 8.10 shows the GWP, CEU for mussel and oyster farming according to the data acquired from Fry (2012) with added primary data on labour from the two Scottish farms that were able to provide it. GWP was very low at 331kg CO_2eq and 1002 kg CO_2eq for mussels and oysters respectively. The energy consumption matched the GWP closely but it is worth noting that the energy mix used was a UK mix rather than Scottish, which is likely to be constituted of a larger proportion of renewables than the UK, which would lead to a lower GWP overall. This would affect oysters much more than mussels as electricity contributes to the GWP of oysters (39%) a lot more than to that of mussels (9%). Oysters are also much more labour intensive to produce. However, economy of scale is likely to play a large part. The mussel farm was considerably larger, producing around 1500 tonnes compared to the oyster farm that produced only around 10 tonnes.

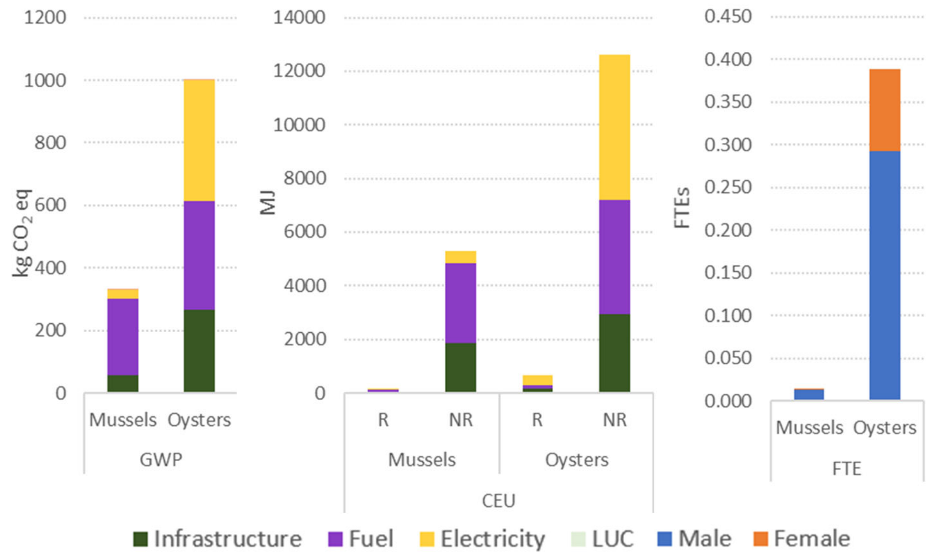

Figure 8.10 Global Warming Potential, Cumulative Energy Use and Labour (FTEs) for Scottish mussel and oyster production.

The data for UK mussel and oyster came from a single processor that processes around 6000 tonnes of shellfish a year. The data for the plant was subdivided where possible into the mussel and oyster streams, and where this was not possible, inputs were allocated by the economic value of the outputs. Most mussels were cooked and not depurated, whereas around half the oysters were depurated and all sold live being the key differences. The LCI for Scottish shellfish processing is shown in Table 8.13.

Table 8.13 Life Cycle inventory of Scottish mussel and oyster processing, per tonne total product

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	Mussels		Oysters	
INPUTS				
Transport (road), tkm	177		130	
Transport (boat), tkm	216		30	
Forklift (LPG), kg	0.974		2.73	
Electricity, kWh	379		92	
Heat (gas), MJ	1084		25.7	
Laminated packaging, kg	0.00226		-	
Cardboard packaging, kg	0.000218		-	
Water, m^3	9.73		0.129	
Male FTE	1.06E-5		2.99E-5	
Female FTE	8.94E-6		2.52E-5	
OUTPUTS		**Allocation %**		**Allocation %**
Live mussels,kg	44	4.6		
Cooked in sauce, kg	640	72.8		
Cooked, plain, kg	256	20.2		
Other, kg	60	2.5		
Depurated oysters, kg	-	-	986	100
Losses	200	0	14	0

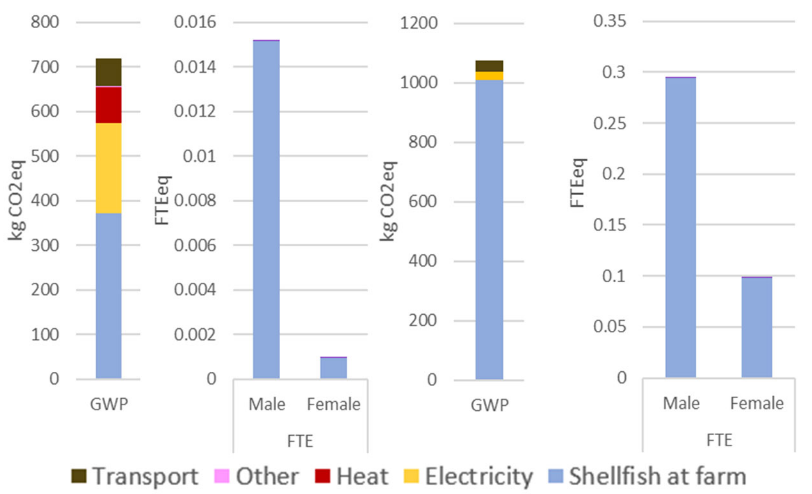

Figure 8.11 Global Warming Potential and employment (FTEeq) of Scottish mussel and oyster production per tonne of total co-products at the processor gate.

Figure 8.11 shows the GWP and employment rate for Scottish shellfish processing. There were considerable energy requirements for the cooking process of mussels, whereas the depuration of (53%) of oysters contributed much less to their overall GWP. Most environmental indicators track GWP closely in terms of their contribution analysis. Table 8.14 provides the indicator values for all impact categories per tonne of product at the processor gate.

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Table 8.14 Selected environmental indicators and employment for Scottish shellfish processing co-products (mussels allocated by economic value) per tonne of product at processor gate.

		Mussels				Oysters	
Impact category	**Unit**	Live	Cooked in sauce	Cooked, plain	Other	Depurated	Non-depurated
GWP	kgCO_2eq	758	825	570	303	1122	1040
CEU (total)	MJ	11841	12880	8901	4727	14959	13783
ODP	kgCFC11eq	8.20E-5	8.91E-5	6.16E-5	3.27E-5	9.83E-5	9.04E-5
PCO	kg C_2H_4eq	0.19	0.21	0.14	0.08	0.34	0.32
AP	kg SO_2eq	3.55	3.86	2.67	1.42	5.58	5.20
LU	m^2/a	115	125	86.4	45.9	176	162
CWU	m^3	13.6	14.8	10.2	5.41	6.83	6.37
FTE (total)	FTEs	0.017	0.019	0.013	0.007	0.395	0.389

The environmental impacts of shellfish production are relatively low compared to salmon and carp production, unsurprisingly because of the lack of feed inputs that make up a considerable contribution to both finfish species. Most of the contributions to all impact categories come from fuel to service the farms and infrastructure that must be maintained, in the case of oysters. According to (Yaghubi *et al.*, 2021) the energy content of farmed mussels is 4380MJ/tonne giving it an EROI of 0.81, where as the energy content of oysters is 3140 MJ/tonne (Krzynoek and Murphy, 1987) giving it an EROI of 0.24, although there is likely to be considerable variation depending on location, season and other factors. Labour was also more intensive for oyster production that had a productivity of only 2.57 tonnes per FTE compared with 69.6 per FTE for mussels. However, a standout point for mussel production was the high level of losses from the farm to processing stage, at around 17% of production. It was claimed that the rejected mussels were all sent to landfill, the impacts of which was not investigated but is a significant area for improvement. Losses from oyster production were only 2% in comparison.

8.4 Novel Ingredient Assessment

As part of GAIN WP1, Sparos and other partners conducted nutrition trials on salmon, trout, seabass, seabream and turbot using novel feed ingredients. The data from the nutrition trials were used to assess the sustainability of the test diets. The intention of these trials was to test the sustainability impacts against industry benchmarks. However, due to COVID19 and travel restrictions, of the species assessed within the feed trials, only Norwegian salmon has been benchmarked. Despite this setback, all nutrition trial data was assessed for standard LCA impact indicators, as well as some added aquaculture specific indictors, such as eFIFO, BRU, water consumption and land use plus detail on the use of renewable vs non renewable energy consumption.

Novel ingredients were a diverse range including insect meals (*Hermetia Illucens and Tenebrio molitor*), various heterotrophic, phototrophic and methanotrophic single cell proteins, macroalgae biomass, microalgae oils as well as more traditional by-product based meals and hydrolysed protein from terrestrial and fishery resources. The differentiation for the trials was mostly between these resources; the Processed Animal Proteins (PAPs) and the non-PAPs which were the aforementioned novel ingredients. The nutrition trials did not run for a full cycle of production so it is difficult to know for certain the full impact, however the results do give a useful indication of the environmental

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performance of novel feed ingredients in aquaculture feeds. A full description of the nutrition trial results can be found in Deliverables D1.2 and D1.5.

8.4.1 Salmon trials

All salmon nutrition trials took place at the GIFAS research station in Indyrr, Norway. The full formulations of the different diets can be seen in Annex 2. Table 8.15 shows a summary of the formulations used in Salmon trial 1.

Table 8.15 Aggregated formulation of diets in salmon feed trial 1

	CTRL	NOPAP	PAP
Mar meals	19	7.5	7.5
Mar oils	6.5	9.25	9.25
Veg meals	50.1	35.4	20.2
Veg oils	18.5	13.4	11.9
PAPs	0	0	19
Insects	0	10	10
Single cell	0	17	15
Macro algae	0	1	2
AAs	1.4	1.9	0.96
Vits and mins	4.53	4.53	4.23
FCR	1.212	1.228	1.242

As well as the inclusion of novel feed ingredients in the PAP and NOPAP diets, the notable difference compared to the control was that all marine meals were from by-products or hydrolysed by-products and some of the traditional forage fish based fish oil was replaced by salmon by-product oil.

The results show a much higher GWP related to higher energy consumption with diets including novel feed ingredients (Figure 8.12). The use of single cell proteins and microalgae oils particularly contribute to the much higher GWP even when LUC is taken into consideration, despite the level of certification in Norwegian production.

The slight shift towards local renewable energy is not enough to off-set the large rise in energy requirements, although an average European energy mix was assumed rather than Norwegian.

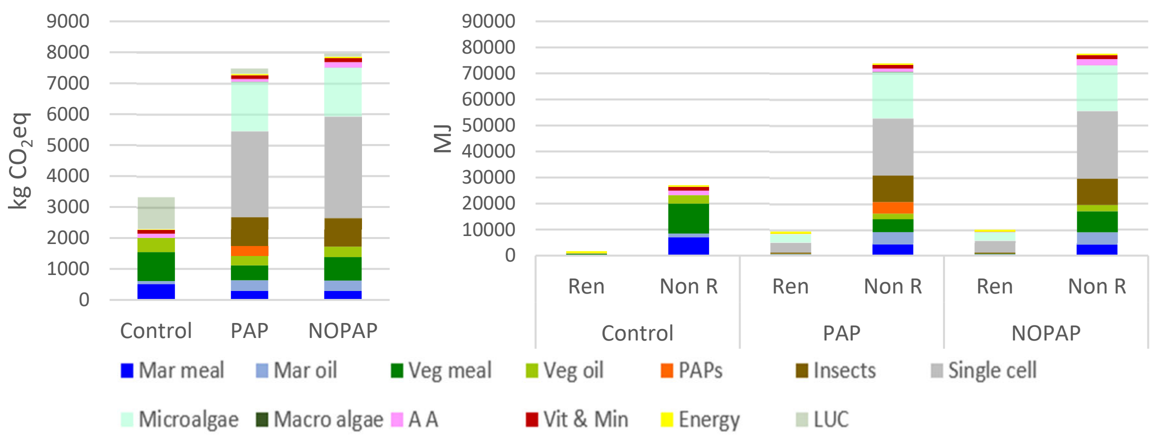

Figure 8.12 Global Warming Potential and Cumulative Energy Use (Ren = renewable, Non R = non-renewable) of salmon production using three trial diets, 1 tonne at "farm gate"

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However, as can be seen from Figure 8.13, if the main goal of "sustainability" is to reduce eFIFO impacts then both the trial diets succeed. There is clearly a debate to be had about global vs local impacts and shifting of the impacts both geographically and in character. Novel ingredient based diets increase both local and global impacts from eutrophication and global warming emissions respectively, but if more renewable energy was used, some global warming emissions could be mitigated. The eutrophication from effluents are the direct emissions from the metabolic activities of fish at the farm, so higher FCRs result in higher effluent discharge, though less digestibility and more waste. In some cases this could be synonymous with benthic impact, but as Section 7 showed, the highly variable current speed has a major effect on the build-up of organic carbon. Figure 8.14 shows that there are clear sustainability gains that could be made in water consumption and land use reduction. However, these come from reducing the quantity and associated impacts from vegetable proteins and meals within the diet, and not from replacing marine ingredients.

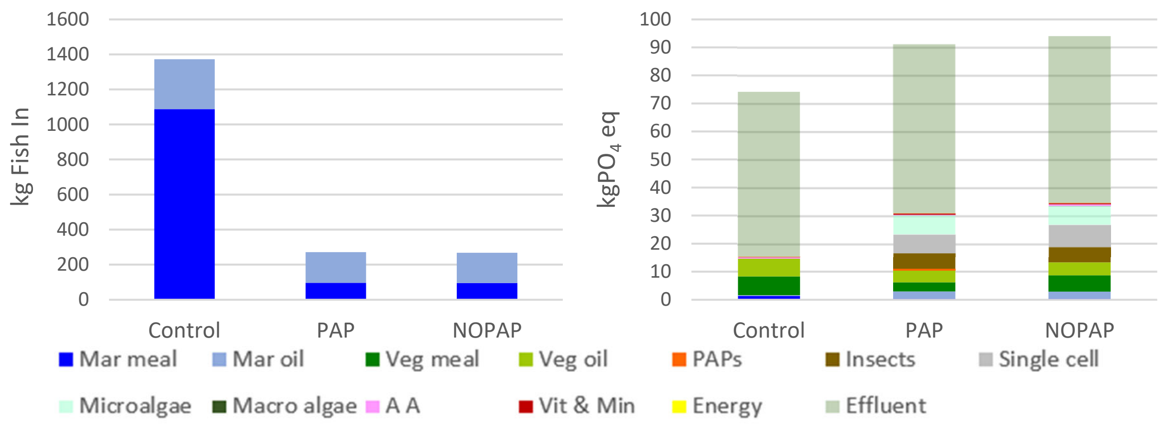

Figure 8.13 eFIFO and Eutrophication Potential of salmon production using three trial diets, 1 tonne at "farm gate"

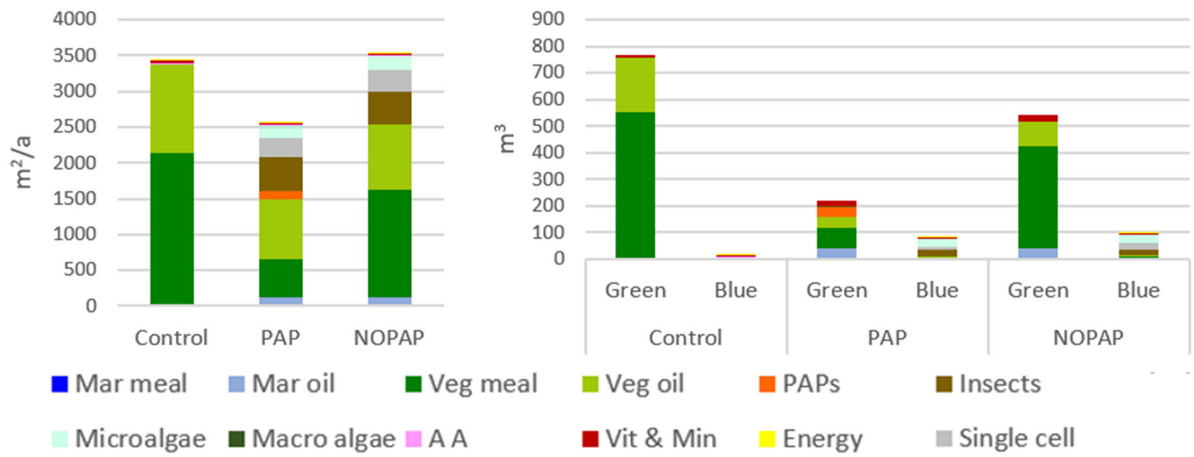

Figure 8.14 Land use and Consumptive Water Use of salmon produced using three trial diets, 1 tonne at "farm gate"

However, it should be noted that the reduction in overall water consumption is tempered from a shift in green to blue water, i.e. precipitation to extraction which may cause more localised sustainability

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concerns. Although green water cannot be considered a “free resource” and any use of this water results in reduced recharge of water channels, its use is not considered as problematic as blue water abstraction which can be from severely water stressed locations that is leading to ecological and public health challenges (Pfister *et al.*, 2011).

Table 8.16 shows the formulations of diets included in the second nutrition trial, also conducted at GIFAS. The control diet is broadly similar to that of the first round of trials with large amounts of vegetable proteins and oils, and marine ingredients slightly lower than found within the commercial diets assessed as part of the benchmarking. Both the PAP and NOPAP diets have substitutions with single cell proteins and insect meals. There is also inclusion of heterotrophic algal oil (included in the single cell category in table 8.16) at around 2.5% and macroalgae at 1.8% in the non-control diets. The NOPAP plus diet has lower substitution of marine meals, whereas the PAP minus diet has the same level of substitution, with more coming from PAPs with no insect inclusion and low levels of single cell proteins, with most of the single cell input coming from heterotrophic algal oil. The full ingredients lists can be seen in Annex 2.

Table 8.16 Aggregated formulation of diets in salmon feed trial 2

	CTRL	NOPAP	PAP	NOPAP+	PAP-
Mar meals	17	2	2	17	2
Mar oils	7	3.5	3.5	3.5	3.5
Veg meals	50.98	38.66	19.41	37.73	30.34
Veg oils	20.5	21.55	20.35	20.05	21.35
PAPs	0	0	21.5	0	34.75
Insects	0	12.5	12.5	6.25	0
Single cell	0	14.55	14.65	9	1.75
Macro algae	0	1.8	1.8	1.8	1.8
AAs	1.5	1.72	1.27	1.85	1.64
Vits and mins	3.03	3.73	3.03	2.83	2.88
FCR	1.10	1.18	1.03	1.22	1.22

The results show some similar trends to the first trial, although there is a more pronounced difference in the FCR between the diets. The control diet performs better than all trial diets on GWP when LUC is not considered but not as well as the PAP minus diet when LUC is considered (Figure 8.15). Large, disproportionate impacts particularly from single cell ingredient inclusions are mostly responsible for the higher GWP and energy consumption. In the PAP minus diet, single cell ingredients account for 39% of the GWP, even though they make up less than 2% of the dietary inclusion by mass. Insect meal (*Hermetia illucens*) also shows a large contribution. Section 8.4.6 shows a more detailed comparison of the individual novel feed ingredients along with data sources.

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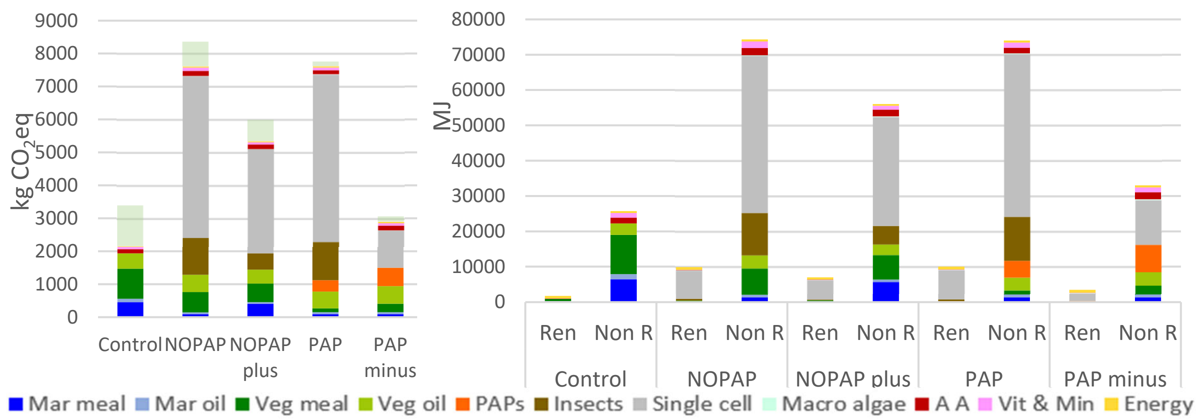

Figure 8.15 Global Warming Potential and Cumulative Energy Use (Ren = renewable, Non R = non-renewable) of salmon production using five trial diets, 1 tonne at "farm gate"

The second round of salmon trials also showed a trade-off between eFIFO and other impacts (Figure 8.16) as would be expected as marine ingredients are substituted for PAPs and novel feed ingredients. The change in FCR between the diets indicates that there could also be some trade-off between localised eutrophication vs more regional or global eutrophication and other impacts. Clearly, if salmon aquaculture production is to grow, there needs to be diet reformulation to reduce inclusions of traditional marine ingredient resources as there are not enough to support current inclusion levels along with higher production. However, the LCA data suggests that there could be far greater GWP, land use and blue water use impacts (Figure 8.17). Overall, the PAP minus diet shows a large reduction in green water with only a modest rise in blue water but has the second largest land use footprint. However, the PAP inclusion accounts for around 19% of GWP emissions and 6% of land use, despite an inclusion rate of nearly 35% in the PAP minus diet. The data would suggest that overall, PAPs are a good choice for substituting marine and vegetable proteins within salmon diets. However, the FCR data indicate that there may be some unforeseen interaction with other ingredients that is not possible to understand from these trials. Whereas the PAP diet had the lowest FCR, the PAP minus diet had the joint highest, which has a considerable influence on the LCA results. In trial 1, all diets had similar FCRs. It would be useful to conduct nutrition trials, incorporating ingredients on an incremental basis to fully understand the interaction effects between diets and the consequences for their environmental impact.

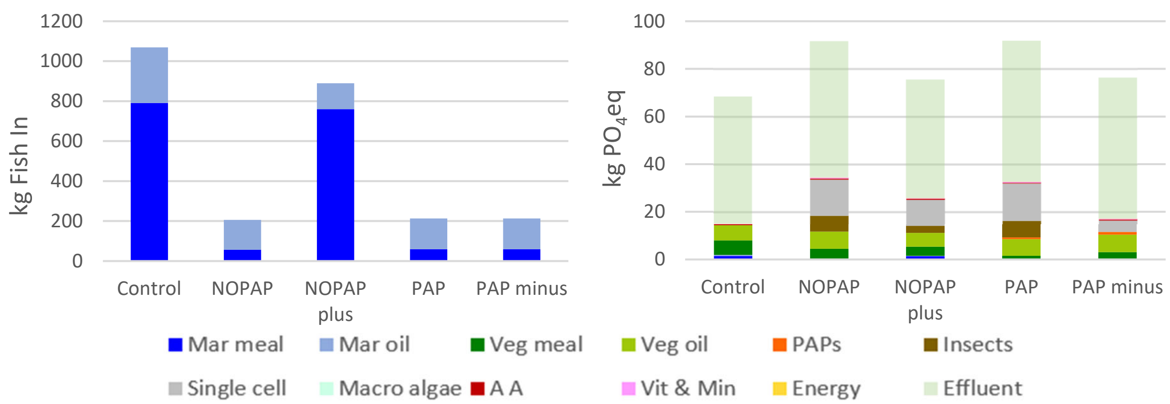

Figure 8.16 eFIFO and Eutrophication Potential of salmon production using five trial diets from salmon trial 2, 1 tonne at "farm gate"

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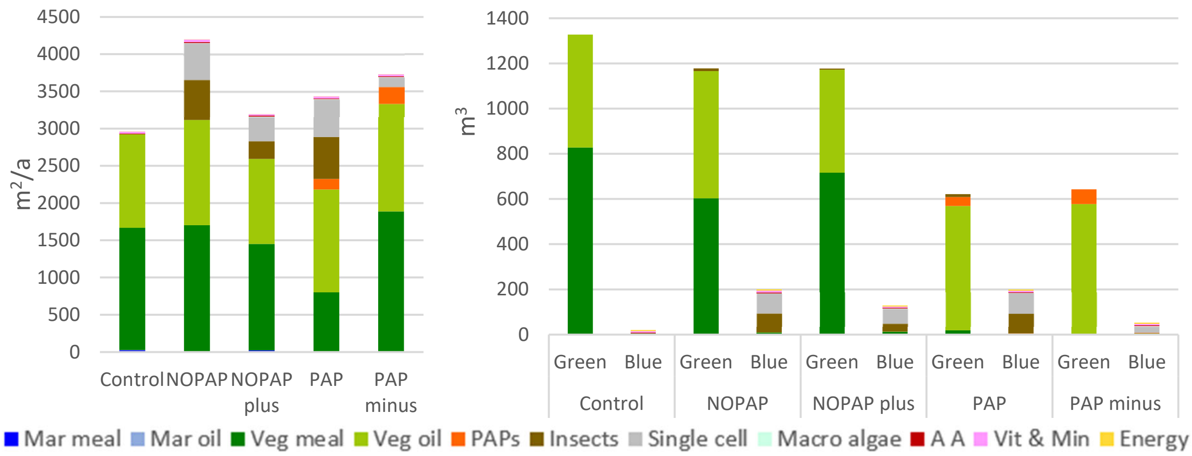

Figure 8.17 Land Use and Water consumption impacts of salmon production using five trial diets from salmon trial 2, 1 tonne at "farm gate"

8.4.2 Trout trials

Two rounds of nutrition trials were conducted with trout using novel ingredient formulations. Table 8.17 shows the aggregated formulations for the first trial (see Annex 2 for full formulation). The FCR is also provided for each diet, which was lower than expected commercial norms that would be expected to be in the region of 1.1 to 1.3. The control diet had large inclusions of fishmeal and soybean meal which were substitute for PAPs, single cell proteins and insect meals. Forage fish marine oils were partially substituted for salmon by-product oil and microalgae oils were present in all test diets.

Table 8.17 Aggregated formulation of diets used in first round of trout nutrition trials

	CTRL	NOPAP	PAP	MIX
Mar meals	23.000	8.000	8.000	3.000
Mar oils	7.400	11.700	11.700	11.700
Veg meals	51.000	38.750	21.950	19.250
Veg oils	13.800	6.900	4.100	4.700
PAPs	0.000	0.000	27.500	17.500
Insects	0.000	5.000	5.000	10.000
Single cell	0.000	17.500	12.000	22.500
Macro algae	0	1	1	1
Micro algae	0.000	3.200	3.200	3.200
AAs	0.55	2.25	1.4	2.1
Vits and mins	4.250	5.700	4.150	5.050
FCR	0.761	0.783	0.784	0.794

Figure 8.18 shows the GWP and CEU of trout produced from experimental diets in the first round of trials. The control diet has much better performance in terms of energy use than the experimental diets which is most responsible for higher GWP. Some of the extra energy is from renewable resources

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but not enough to make up for the much larger energy requirements for non-renewable energy across European mixes.

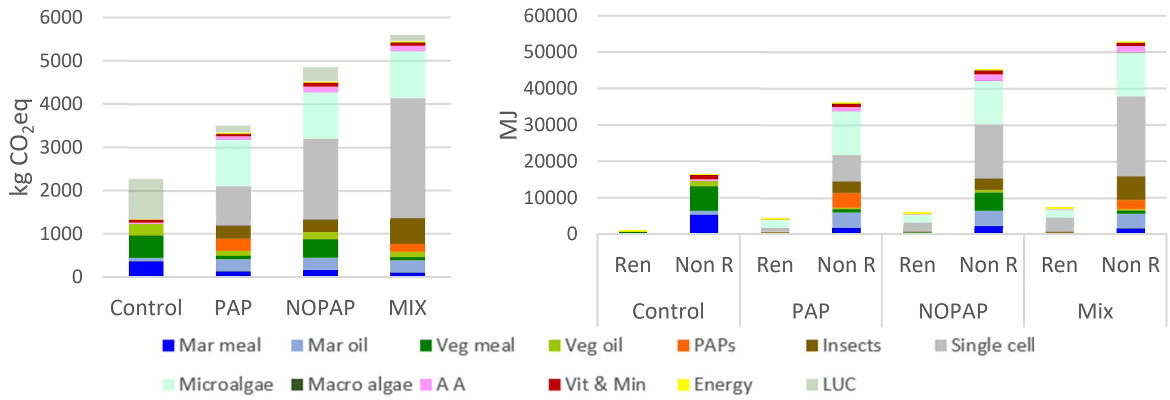

Figure 8.18 Global Warming Potential and Cumulative Energy Use (Ren = renewable, Non R = non-renewable) of trout production using four trial diets from the first round of trials, 1 tonne at "farm gate"

Figure 8.19 shows the BRU and eutrophication potential from the four experimental diets used in the first round of trials. BRU and eFIFO, largely track each other, however BRU is lower if marine ingredients are sourced from lower trophic species and shows a slightly different composition compared to FIFO. BRU also includes resources that are not marine, i.e. the primary production associated with land use change. However, FIFO provides a more tangible metric for policy makers. BRU was chosen in this instance to provide some slightly different insights compared to the analysis shown for salmon in Section 8.4.1. The eFIFO for the control diet was 0.872 with other diets proportionately lower as for BRU. BRU has a slight weighting towards fish meals compare to oils because of the higher trophic species included in meals overall. Eutrophication is only slightly affected by FCR at the farm compared to higher emissions within the supply chain, mostly related to energy provision.

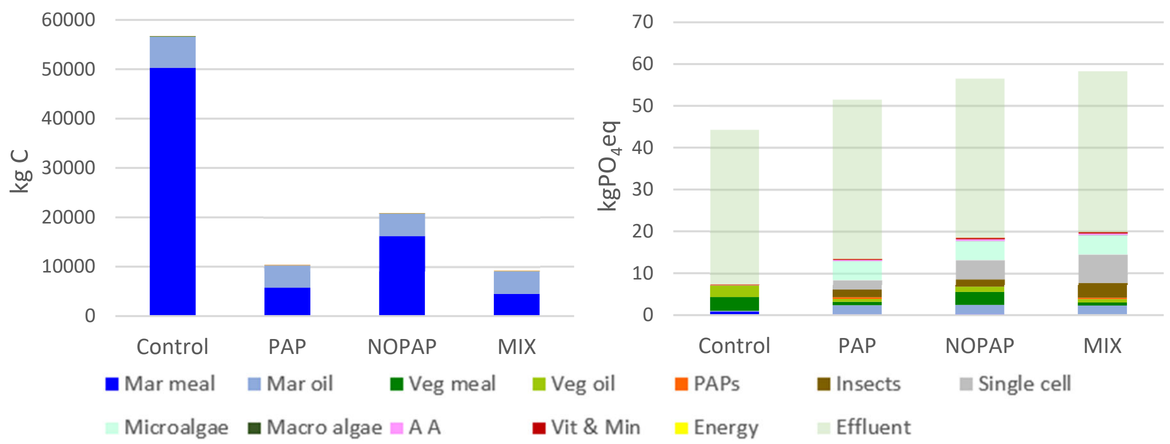

Figure 8.19 Biotic Resource Use and Eutrophication Potential from trout production using four experimental diets in trout trial 1, 1 tonne at "farm gate"

The effects on land and water use are mixed between the diets (Figure 8.20). There are some small gains to be made on land use with the PAP and MIX diet and considerable savings on green water use, but again this comes at the cost of much more blue water use for the experimental diets, from single cell proteins, insects and microalgae oils.

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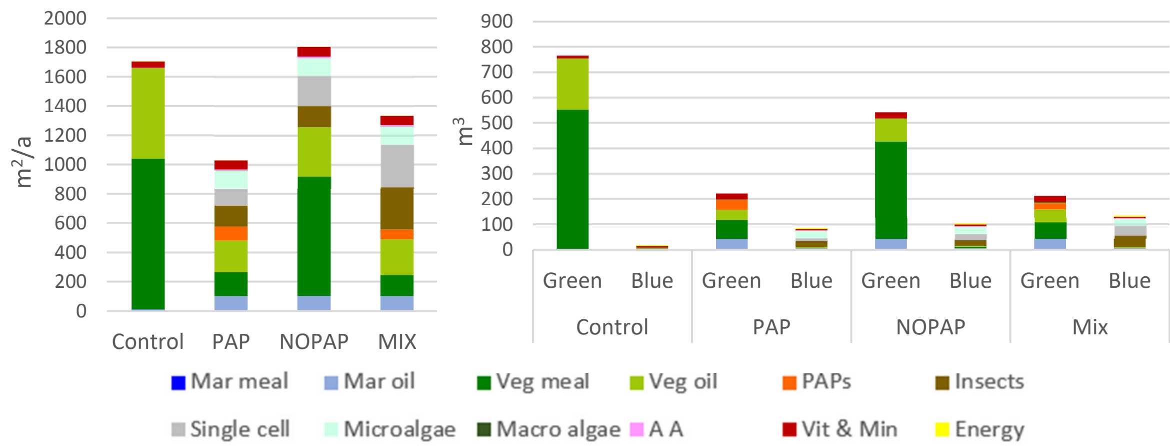

Figure 8.20 Land Use and Consumptive Water Use from trout production using four experimental diets in trout trial 1, 1 tonne at "farm gate"

Table 8.18 show the aggregated formulation of diets used in the second round of trout nutrition trial. Marine meals were substituted in all diets except the NOPAP plus diet by PAPS and novel feed ingredients, and forage fish and vegetable oils were replaced by salmon by-product oils.

Table 8.18 Aggregated formulation of diets used in the second round of trout nutrition trials

	CTRL	PAP	NOPAP	NOPAP+	PAP -
Mar meals	17.000	2.000	2.000	19.000	2.000
Mar oils	5.300	12.650	12.650	12.650	12.650
Veg meals	58.300	47.410	25.580	36.750	32.590
Veg oils	16.200	7.700	5.900	6.000	6.100
PAPs	0.000	0.000	25.000	0.000	29.000
Insects	0.000	16.000	16.000	10.000	5.000
Single cell	0.000	6.200	6.300	10.200	5.300
Macro algae	0.00	2.05	2.05	2.05	2.05
Micro algae	0.000	1.000	1.000	1.000	1.000
AAs	0.71	0.78	0.57	0.20	0.96
Vits and mins	2.490	4.210	2.950	2.150	3.350
FCR	0..817	0.831	0.844	0.769	0.873

The results show that all experiments diets have larger GWPs than the control when LUC is not included and only the diets containing PAPs had lower GWPs when LUC is included (Figure 8.21). The high energy demand of single cell proteins, insect meals and microalgae oils are the main contributors to elevated energy demand, especially non-renewables. Larger GWP from marine oils are due to the use of salmon by-product oils which are assumed to be a co-product from hydrolysation which is more energy intensive than traditional fishmeal and oil co-production. BRU and FIFO tend to track each other fairly closely as the contribution from terrestrial ingredients is very low for BRU and zero for FIFO. The eFIFO for fish produced in the trout trials ranged from 0.133 to 0.758 for the PAP diet and

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NOPAP plus respectively. In the second trout trial, there was a discrepancy in that the control diet has a higher BRU but lower eFIFO than the NOPAP plus diet which is due to the inclusion of krill meal in the NOPAP plus diet which has a lower trophic level but poor yields at the rendering stage, resulting in the higher eFIFO compared to more traditional fishmeal resources.

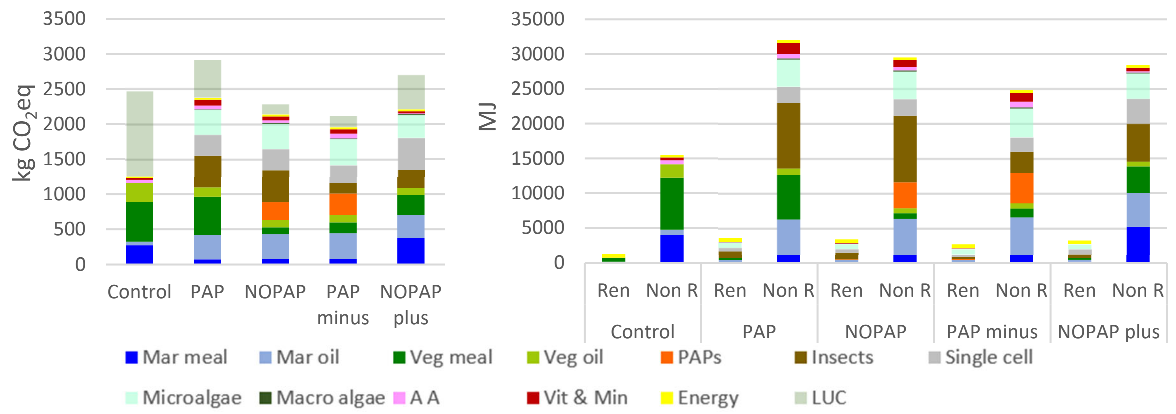

Figure 8.21 Global Warming Potential and Cumulative Energy Use (Ren = renewable, Non R = non-renewable) of trout production using five trial diets from the second round of trials, 1 tonne at "farm gate"

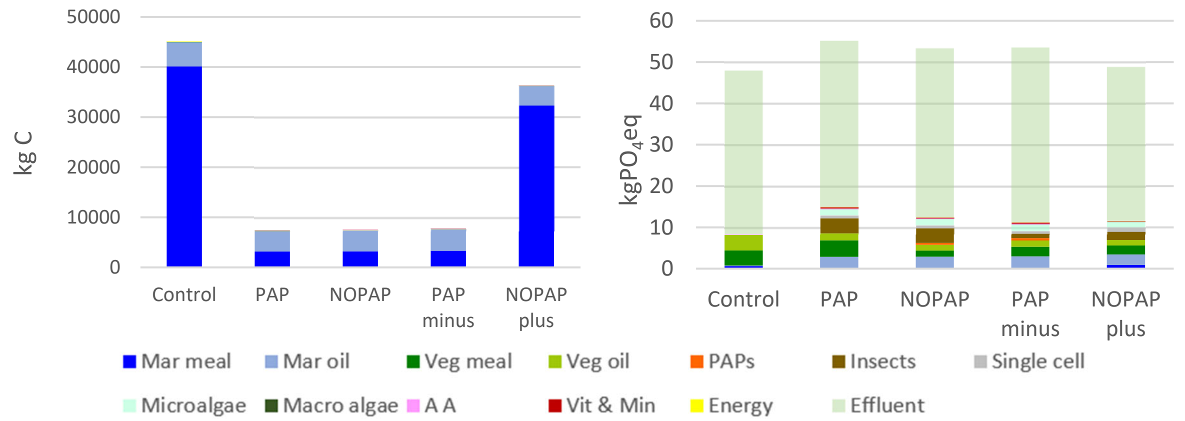

Figure 8.22 Biotic Resource Use and Eutrophication Potential from trout production using five experimental diets in trout trial 2, 1 tonne at "farm gate"

The PAP diet showed increased eutrophication (Figure 8.22) and land use (Figure 8.23), particularly related to the inclusion of insect meals. Water consumption was reduced across all the experimental diets, albeit with a slight shift to blue water. Overall, across the six environmental impact categories, the PAP minus diets showed equivalent or a reduced emissions/ resource use compared to the control, but a larger FCR contributed to slightly higher eutrophication both in diet formulation and from resulting effluent at the farm.

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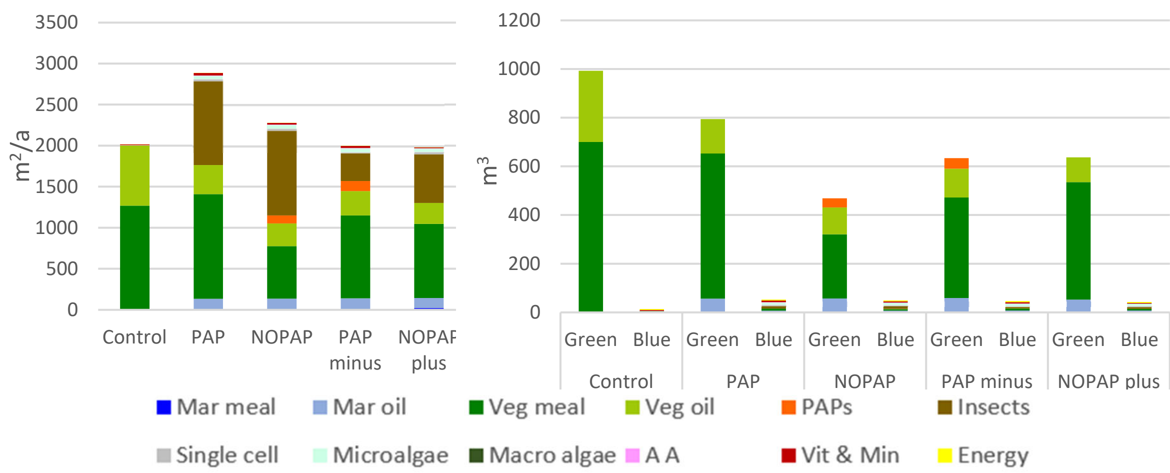

Figure 8.23 Land Use and Consumptive Water Use from trout production using five experimental diets in trout trial 2, 1 tonne at "farm gate"

8.4.3 Seabass Trials

There was only one round of nutrition trials conducted on seabass. The aggregated formulation for the diets is given in Table 8.19. The experimental diets have large amounts of marine meals substitute by PAPs, insects and single cell proteins, apart from the NOPAP plus diet which has large amounts of marine ingredients as well as insect meals and single cell proteins. Much of the vegetable oil was substituted by salmon by-product oil (assumed to be from the hydrolysis process). All the experimental diets had inclusions of macroalgae biomass.

Table 8.19 Aggregated formulation of diets used in seabass nutrition trials

	CTRL	PAP	NOPAP	NOPAP+	PAP -
Mar meals	18.000	3.000	3.000	23.000	3.000
Mar oils	5.400	11.700	11.700	16.200	11.700
Veg meals	50.800	34.730	25.910	24.540	37.890
Veg oils	12.700	5.900	5.100	0.000	4.900
PAPs	10.000	0.000	21.250	0.000	34.000
Insects	0.000	15.000	10.000	13.500	0.000
Single cell	0.000	20.200	15.200	16.200	0.200
Macro algae	0.00	2.60	2.60	2.60	2.60
Micro algae	0.000	1.000	1.000	1.000	1.000
AAs	0.30	1.37	0.64	0.01	1.36
Vits and mins	2.800	4.500	3.600	2.950	3.350
FCR	1.06	1.12	0.96	1.14	1.10

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Figure 8.24 shows the GWP and CEU from the seabass nutrition trials. The PAP minus is clearly the best performer among the experimental diets compared to the control. Other experimental diets have GWPs up to three or five times higher, depending on whether LUC is included. Energy consumption for the PAP minus diet is higher than the control but potential LUC is considerably lower as all soybean ingredients and many other vegetable ingredients have been completely substituted. Figure 8.25 shows the eFIFO and Eutrophication Potential for the seabass nutrition trial. FIFO is highest for the NOPAP plus diet with the large marine ingredient inclusion. Despite a lot coming from by-product resources, there was a larger inclusion of conventional fishmeal and krill meal. The NOPAP plus diet also had the highest FCR of all the feeds, which is surprising, considering the high quantity of marine ingredients. This may be partly to do with the lower quality of by-product marine ingredients, the inclusion of insect meals or single cell proteins, all of which have lower digestibilities.

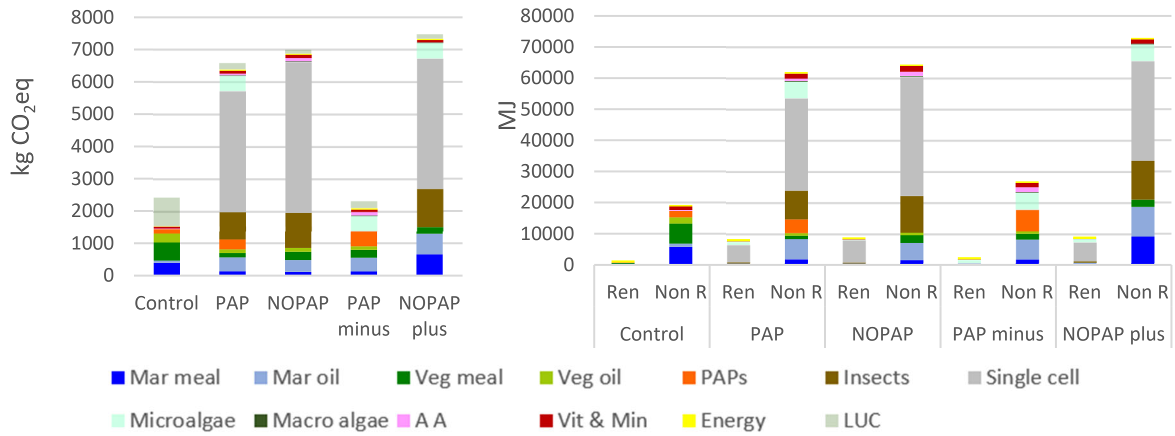

Figure 8.24 Global Warming Potential and Cumulative Energy Use (Ren = renewable, Non R = non-renewable) of seabass production using five trial diets, 1 tonne at "farm gate"

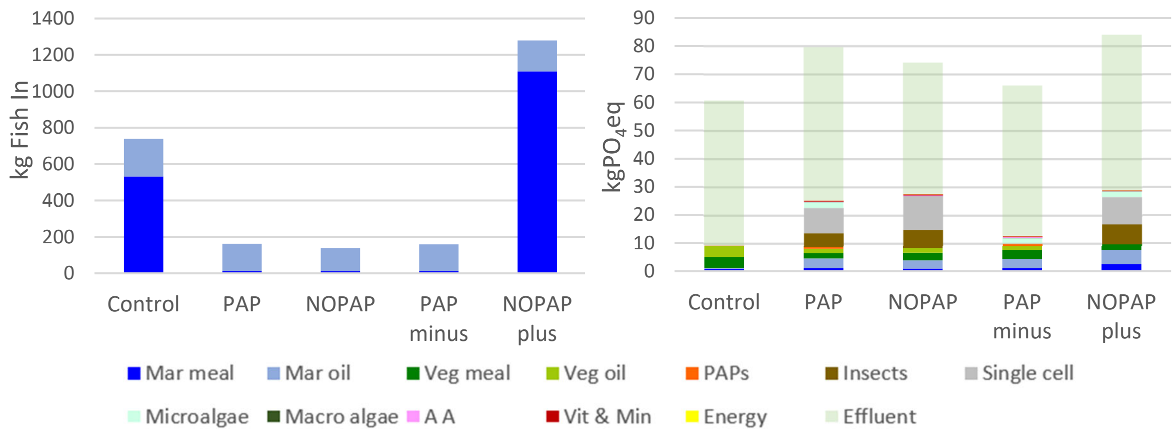

Figure 8.25 Fish In Fish Out ratio and Eutrophication Potential of seabass production from five experimental diets, 1 tonne at "farm gate"

The PAP minus is the most promising diet in terms of lower FIFO and Eutrophication Potential and also has the lowest Land Use of all five diets. Fish produced on the NOPAP diet is the only case in which the eFIFO is greater than 1 (1279 kg of fish in per 1000kg of fish produced), showing it to be a net consumer of fish where all others are net producers. Water consumption (combined blue and green) is second highest for the PAP minus diet after the control diet, but it has the second lowest blue water

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consumption after the control diet (Figure 8.26). Green water contributions from marine ingredients are related to the embodied water coming from by-product value chains for hydrolysate and oil co-production. Overall, the PAP minus diet seems to perform best across all impact categories, after the control diet, and the NOPAP plus diet is the worst with the highest impact in five of the six categories presented in this analysis.

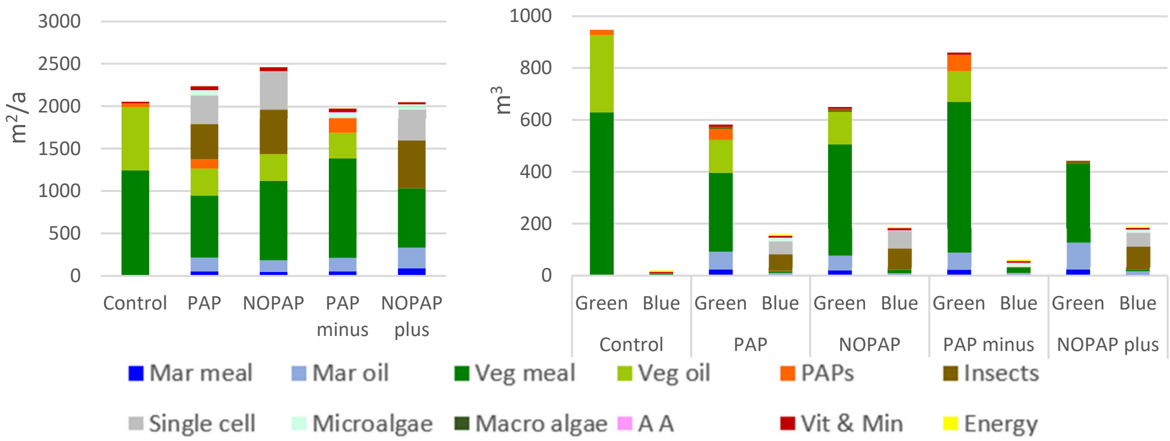

Figure 8.26 Land Use and Consumptive Water Use of seabass production from five experimental diets, 1 tonne at "farm gate"

8.4.4 Seabream diets

There was only one seabream nutrition trial, although a health challenge trial was conducted which is not included in this analysis. The aggregated formulations for the seabream diets are given in Table 8.20. The control formulation had very large inclusions of marine and vegetable meals which were mainly substituted for by PAPs or single cell proteins with some insect inclusion also. Marine oils were partially replaced by microalgae oil. FCRs were higher than for other fish species reported in earlier sections but within the expected range for seabream.

Table 8.20 Aggregated formulation of diets used in seabream nutrition trials

	CTRL	MIX	PAP	NOPAP
Mar meals	20.000	5.000	5.000	10.000
Mar oils	6.000	3.000	3.000	3.000
Veg meals	56.670	24.430	30.780	45.500
Veg oils	8.260	6.300	6.000	8.500
PAPs	5.000	18.000	28.000	0.000
Insects	0.000	10.000	5.000	5.000
Single cell	0.000	22.000	11.500	17.000
Macro algae	0.00	2.00	2.00	2.00
Micro algae	0.000	3.700	3.600	3.200
AAs	0.05	0.95	0.80	0.88
Vits and mins	4.020	4.620	4.320	4.920
FCR	1.40	1.56	1.62	1.48

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The GWPs of seabream fed all experimental diets were higher than that for the control, including when LUC is taken into account. Single cell proteins and microalgae oil are the main contributors to high energy requirements (Figure 8.27).

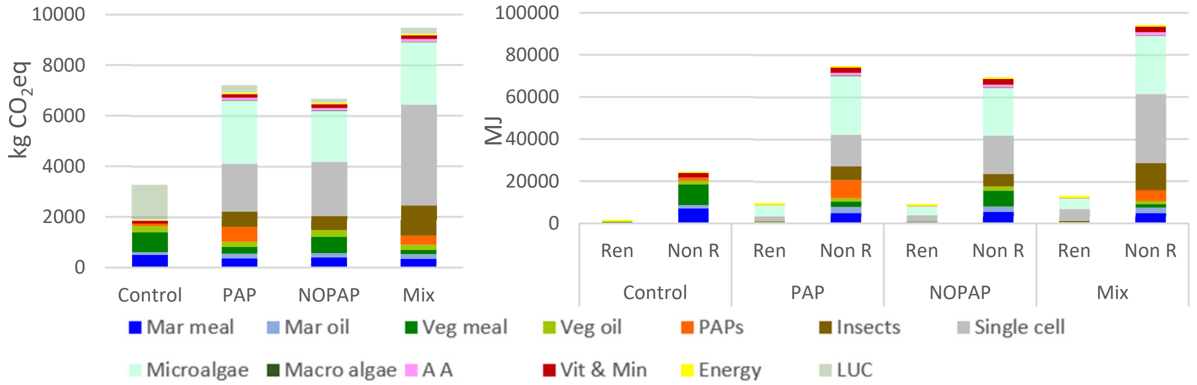

Figure 8.27 Global Warming Potential and Cumulative Energy Use (Ren = renewable, Non R = non-renewable) of seabream production using four trial diets, 1 tonne at "farm gate"

Figure 8.28 shows the FIFO and Eutrophication potentials for seabream produced using the trial diets. The control diet shows high levels of "embodied fish" with an eFIFO of 1.48 (1483 kg embodied fish per tonne of production). Higher eutrophication is partly down to the use of novel ingredients but mainly due to higher FCRs with experimental diets. Water consumption again shows a trade-off between lower green water vs much higher blue water extraction, but land use is much higher for experimental diets vs the control (Figure 8.29). Clearly the main trade-off is the much larger impacts associated with marine ingredient replacement and the sustainability of the supply of those marine ingredients.

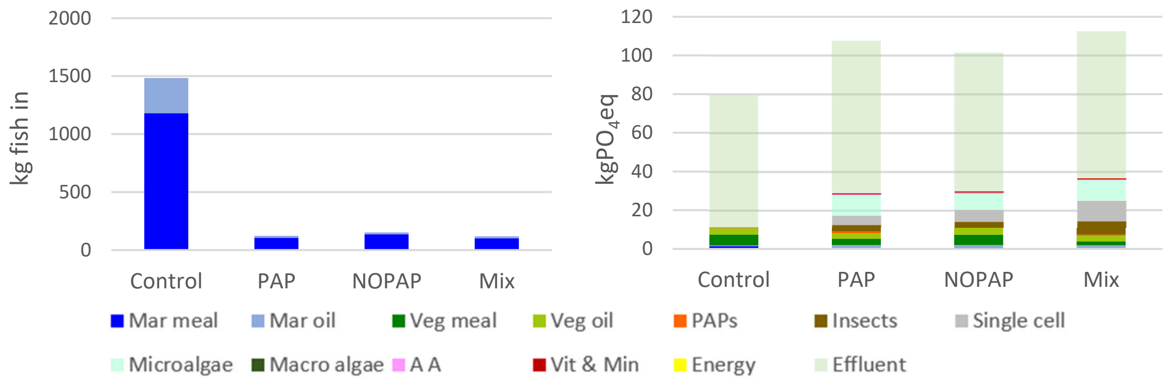

Figure 8.28 Fish In Fish Out ratio and Eutrophication Potential of seabream production from four experimental diets, 1 tonne at "farm gate"

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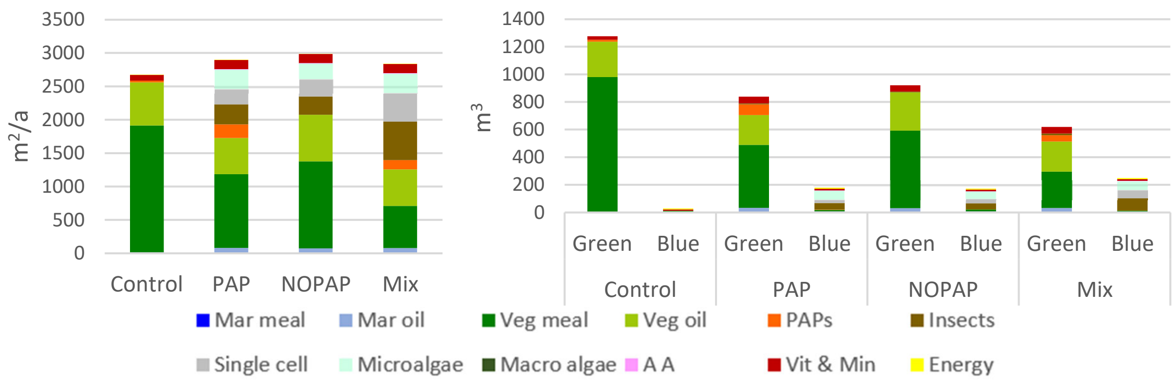

Figure 8.29 Land Use and Consumptive Water Use of seabream production from four experimental diets, 1 tonne at "farm gate"

8.4.5 Turbot

Two turbot nutrition trials were conducted. The aggregated formulations for the diets in the first trial are provided in Table 8.21. Turbot has one of the largest inclusions of marine ingredients in its diet of any species at around 50% and has proven difficult to replace in substantial quantities (Leknes *et al.*, 2012). The experimental diets in the GAIN trials replaced up to 20% of the fishmeal inclusion with single cell protein, insects and PAPs. The quantity of vegetable meal was also reduced, while vegetable oil partially replaced marine oils with the rest from microalgae (Table 8.21).

The experimental diets again show a much larger energy requirement than the control, leading to a GWP that is around double, including LUC, in the worst case (Figure 8.30). There are large gains in FIFO, with experimental diets having much lower eFIFO ratios than the control (Figure 8.31). All other impacts are higher for the experimental diets than the control, showing similar patterns to other trials. There are some small gains in water consumption from the PAP diet but with more coming from blue water abstraction (Figure 8.32).

Table 8.21 Aggregated formulation of diets used in Turbot nutrition trial 1

	CTRL	PAP	NOPAP	MIX
Mar meals	50.000	40.000	30.000	40.000
Mar oils	11.600	4.640	4.640	4.640
Veg meals	37.000	23.990	26.990	32.790
Veg oils	0.000	3.440	3.440	4.640
PAPs	0.000	12.700	7.500	0.000
Insects	0.000	5.000	7.500	5.000
Single cell	0.000	5.000	13.800	7.700
Macro algae	0.00	0.50	0.50	0.50
Micro algae	0.000	1.080	1.880	1.080
AAs	0.00	0.95	1.05	0.95
Vits and mins	1.400	2.700	2.700	2.700
FCR	0.847	0.897	0.877	0.851

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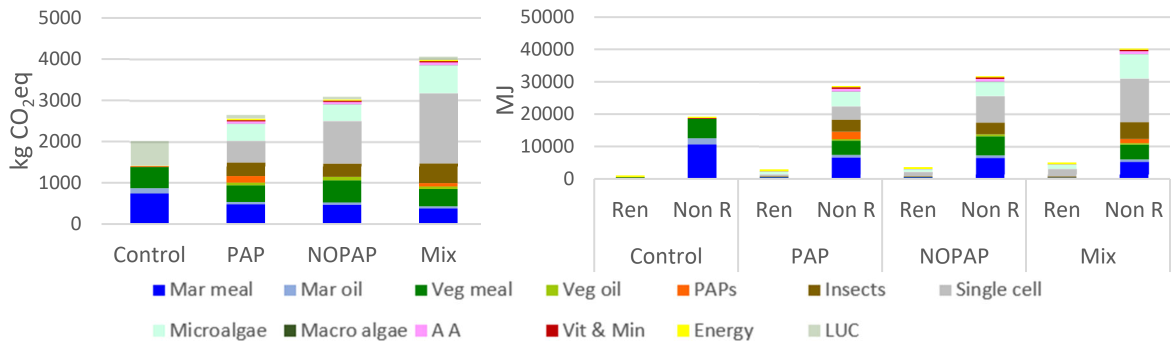

Figure 8.30 Global Warming Potential and Cumulative Energy Use (Ren = renewable, Non R = non-renewable) of turbot production using four trial diets, 1 tonne at "farm gate"

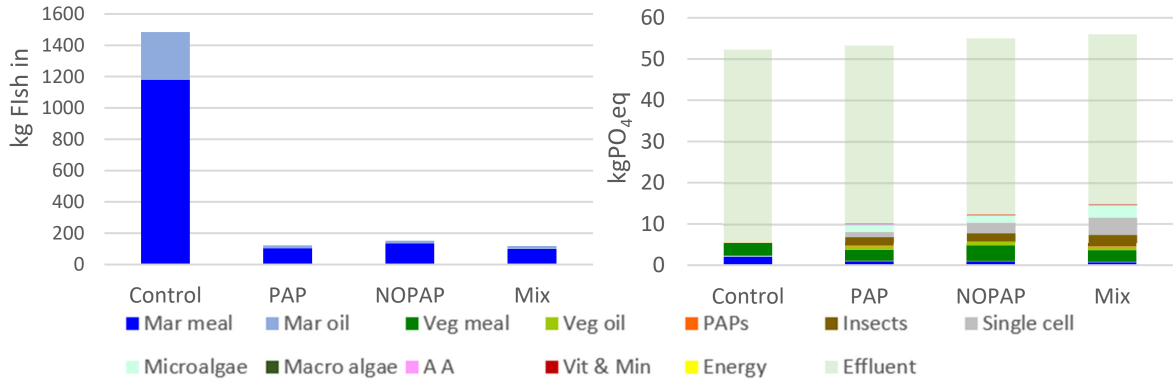

Figure 8.31 Fish In Fish Out ratio and Eutrophication Potential of turbot production from four experimental diets, 1 tonne at "farm gate"

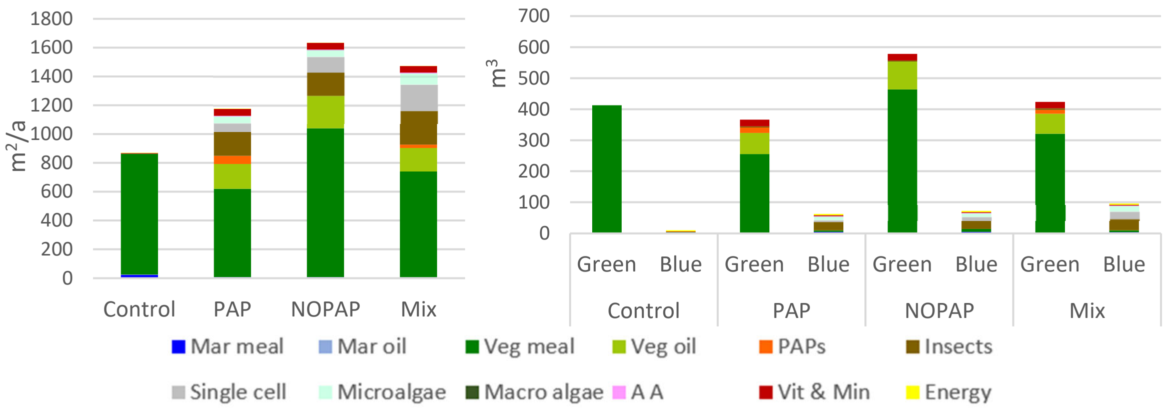

Figure 8.32 Land Use and Consumptive Water Use of turbot production from four experimental diets, 1 tonne at "farm gate"

The diet formulations for the second round of trials can be seen in Table 8.22. Similar to the first round, high levels of marine ingredients and vegetable proteins were substituted for PAPs, insect meals and single cell proteins. Marine oils and some vegetable oils were also substituted for microalgae oil and some salmon by-product oil. The FCRs for the second round were noticeably much higher than those for the first round of trials which leads to much higher impacts overall.

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Table 8.22 Aggregated formulation of diets used in Turbot nutrition trial 2

	CTRL	NO PAP 30	PAP 30	NO PAP 60	PAP 60
Mar meals	44.000	35.500	35.500	23.500	23.500
Mar oils	7.000	7.300	7.300	9.100	9.000
Veg meals	42.030	29.800	12.170	30.330	12.650
Veg oils	4.500	2.700	1.400	1.200	0.000
PAPs	0.000	0.000	21.000	0.000	21.000
Insects	0.000	8.750	8.750	13.700	13.700
Single cell	0.000	9.050	9.050	14.000	14.000
Macro algae	0.00	2.05	2.05	2.05	2.05
Micro algae	0.000	1.000	1.000	1.200	1.200
AAs	0.00	0.88	0.01	1.15	0.23
Vits and mins	2.470	2.970	1.770	3.770	2.670
FCR	1.28	1.47	1.68	1.60	1.75

Figure 8.33 shows the GWP and energy utilisation for fish produced on each of the diets. Fish produced from the PAP 60 and NOPAP 60 diets were the worst performing, with GWPs around four times higher than fish produced on the control diet. The energy consumption and GWP in the PAP diets substituted almost exactly for the energy consumption and GWP from vegetable ingredients in the NOPAP diets, but impacts from single cell protein, insects and microalgae were high among all the diets apart from the control. The energy use and GWP from marine ingredients remained fairly consistent for fish produced from all five diets despite substitution because more energy intensive fish protein concentrates, krill meal and salmon oil were used in place of traditional forage fish meals. The eFIFO for fish produced on the control diet was especially high at 2.60, with all other diets being "net producers" of fish (Figure 8.34). The large FCRs led to a high level of nutrient release at the farm that resulted in high eutrophication as well as the eutrophication potentials from the production of feed ingredients themselves.

Land use was higher than the control diet for all experimental diets except for the PAP30 diet, which had the lowest inclusion of vegetable ingredients (Figure 8.35). the contribution to land use from insect meals was substantial, due to the substrate that insects were being fed on which was mostly by-products from various parts of the wheat value chain. The low inclusion of vegetable ingredients in the PAP 30 and PAP 60 diets also led to much lower water consumption than any other of the diets, including the control although insect meals again had large contributions. This was especially the case in the PAP 60 diet which was the only diet in any of the trials to have used more blue water (extractive) than green water (precipitation).

Overall fish produced on the diets containing novel ingredients showed to have higher GWP, energy usage and eutrophication. Land use and water impacts were more mixed although there was commonly an increase in abstractive water use compared to precipitation. These impact categories were picked because they show the most trade-offs in a small number of categories. Other categories such as Acidification Potential, especially, but also PCO and ODP tend to track GWP because they are often produced from similar processes, especially energy provision. However, energy consumption

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was also chosen as the trade-off between renewables and non-renewables was also regarded important.

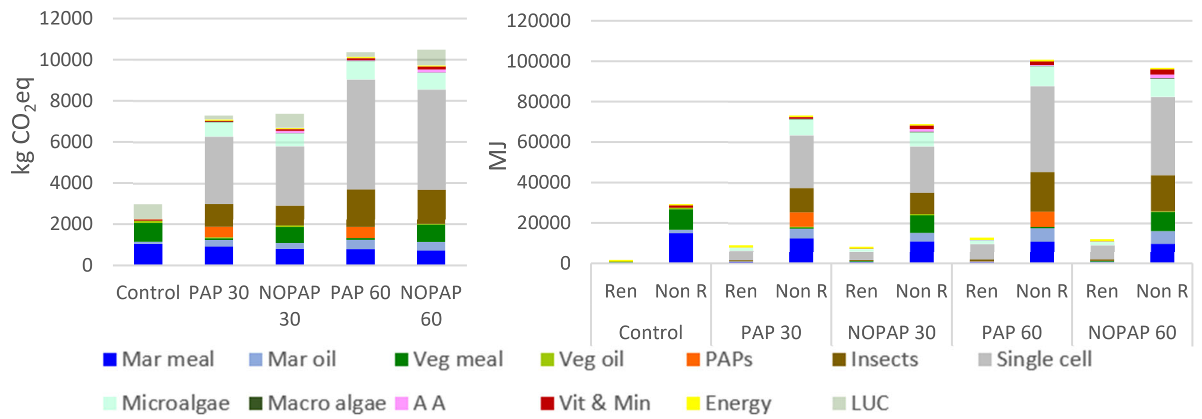

Figure 8.33 Global Warming Potential and Cumulative Energy Use (Ren = renewable, Non R = non-renewable) of turbot production using four trial diets, 1 tonne at "farm gate"

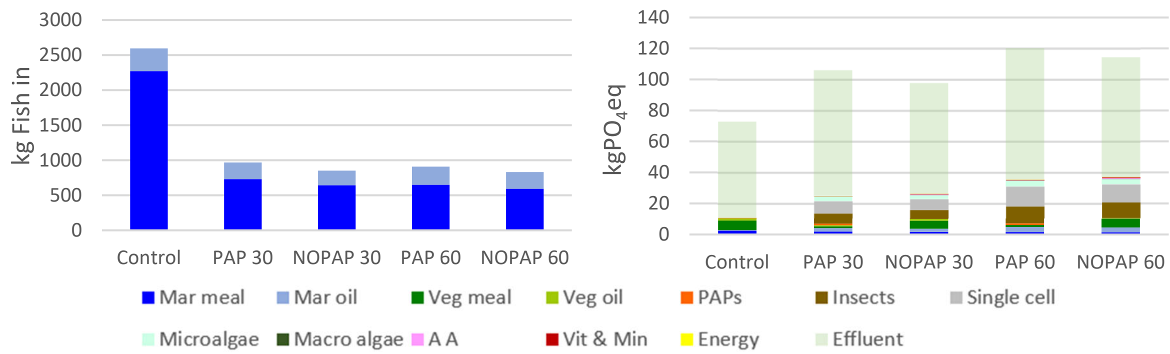

Figure 8.34 Fish in Fish Out ratio and Eutrophication potential of turbot production using five trial diets, 1 tonne at "farm gate"

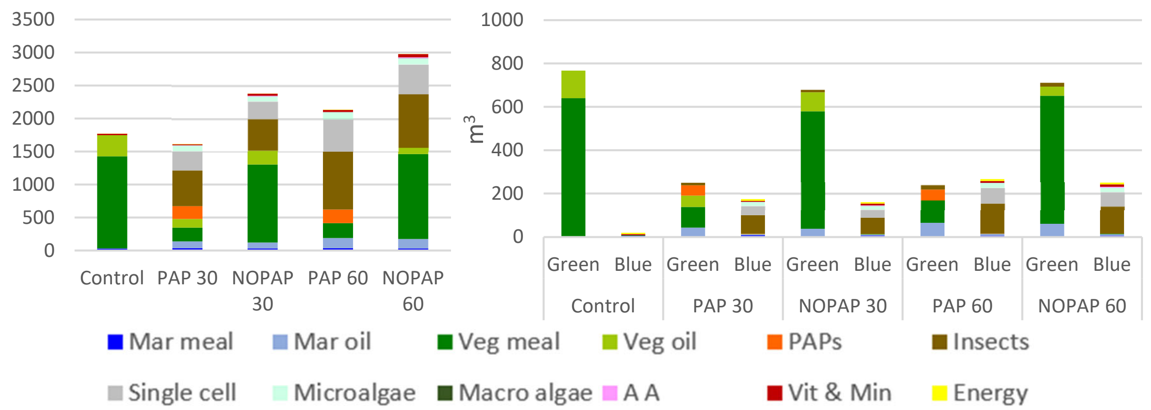

Figure 8.35 Land Use and Consumptive Water Use of turbot production from four experimental diets, 1 tonne at "farm gate"

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8.4.6 Novel feed ingredients

This section shows the impacts of the individual feed ingredients per tonne of production and highlights the trade-off between impacts for those ingredients and the diets included in Sections 8.4.1 to 8.4.5. Figure 8.36 shows the comparative GWP between novel ingredients investigated in the GAIN nutrition trials along with traditional marine, vegetable and PAP ingredients. Clearly, many of the novel ingredients have GWPs way larger than traditional ingredients. Much of the impact is associated with the drying/separation process and/or the provision of substrate. This also stands out for salmon by-product oil which in this case is a co-product from the hydrolysation process, rather than less intensive, traditional pressing and cooking fishmeal and fish oil production methods (Fréon *et al.*, 2017) et al 2017). In the case of insects, Smetana *et al.* (2019) reported that in excess of 30kg of substrate are required to produce 1kg of Black Soldier Fly meal and (Thévenot *et al.*, 2018) reported over 7kg of substrate to produce 1kg of mealworm meal. As the EU regulations view insects as "farmed animals", the substrate has to be of a standard suitable for feeding any other farmed animal rather than waste products. The reliance on large quantities of feed grade substrate to produce insect meals for feed undoubtedly contributes highly to the footprint of insect meals. The reliance on feed grade agricultural products for substrate also has an impact on water use (Figure 8.37), most notably the blue water use in insect production, single cell bacteria and microalgae oil. Soy and rapeseed have much higher water requirements but currently, this is mostly met by green water supply. Likewise, the salmon by-product oil has high green water use associated with the provision of feed for salmon production, in effect the embodied water use from soybean, rapeseed oil and other vegetable ingredients carried through the supply chain.

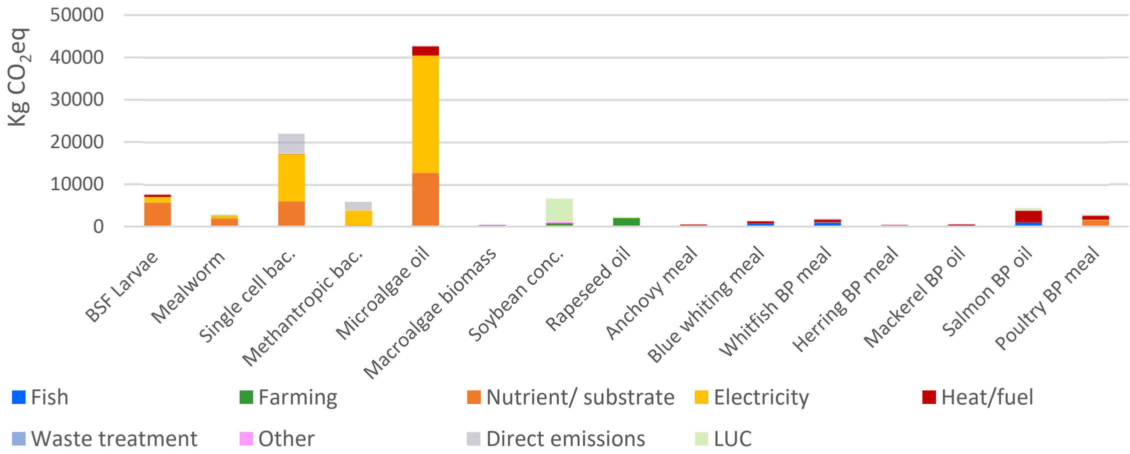

Figure 8.36 Global Warming Potential of novel feed ingredients and selected other meal and oils, per tonne of ingredient (BP = by-product, BSF = black soldier fly) Data as follows: BSF larvae – Smetana et al (2019), mealworm – Thevenot et al (2018), Single cell bacteria/ microalgae – Smetana et al (2017), Järviö et al (2021), Maiolo et al (2020), methantrophic bacteria – Abbadi et al (in press), marine ingredients as reported in D4.4. Poultry BP meal – unpublished data (Newton, 2016).

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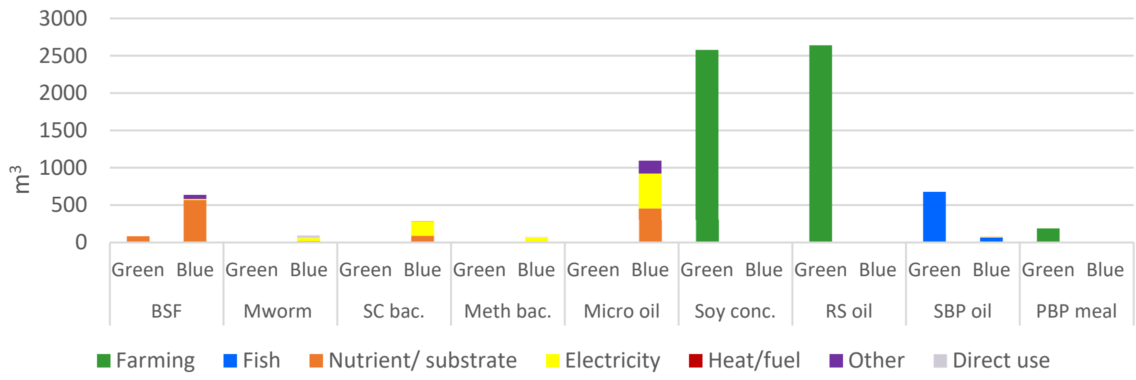

Figure 8.37 Consumptive Water Use of novel feed ingredients and selected other meal and oils, per tonne of ingredient. Note that the water usage of traditional marine ingredients is negligible (BSF = black soldier fly, Mworm = mealworm, SC = single cell, Meth = methanotrophic, RS = rapeseed, SBP = salmon by-product, PBP = poultry by-product). Data as for figure 8.31

Figure 8.38 shows the trade-off between the key sustainability aspects of BRU, GWP and land use. BRU largely tracks FIFO and is chosen in this case because FIFO for marine ingredient alternatives is zero and cannot be plotted on a logarithmic scale as in Figure 8.38. GWP largely tracks many other of the LCA impact categories, including AP, ODP, PCO and EP (Figure 8.39), all of which are connected to energy supply into some degree. Figure 8.38 clearly shows that different ingredients have very different impacts and it is not as simple as saying one ingredient is better than another based on a small set of indicators. There are clear groupings, with marine ingredients having large BRU but small land use and mostly smaller GWP. Insect meals have lower BRU but much higher land use and medium to large GWP, whereas single cell and methantrophic bacteria have high land use and high to very high GWP. Soybean has medium BRU attributed to LUC (not included in GWP calculations) high land use but low GWP. Poultry by-product meal has medium to low and macro-algae is low in all three impact categories. Figure 8.40 shows the same analysis for the different diets that were used in the GAIN nutrition trials and their performance. There is considerable difference between the relative impacts of the diets and their performance for seabass, seabream and turbot but less so for salmon and trout, highlighting that the performance of the diet must be tested as it cannot be predicted from the formulation alone.

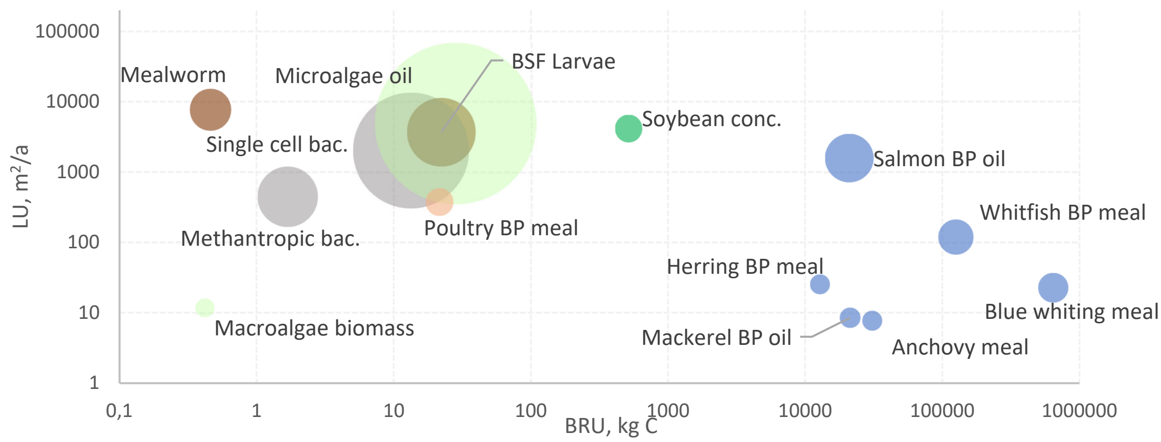

Figure 8.38 Biotic Resource Use, Land Use and relative GWP (bubble size) of novel feed ingredients, soybean protein concentrate and selected marine ingredients.

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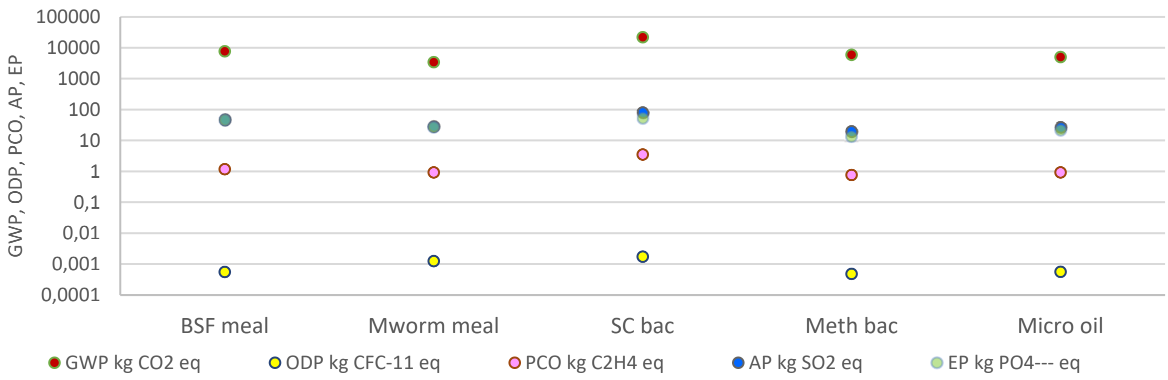

Figure 8.39 Comparison between GWP, ODP, PCO, AP and EP life cycle impacts from novel feed ingredients production (one tonne).

The underlying question around supplying sustainable ingredients to the aquaculture but also other livestock industries is what do we consider to be sustainable? Within the aquaculture literature, there has been a narrow focus on marine ingredients, a perception that they must be replaced and that anything that is not a marine ingredient is "sustainable". Within other livestock production, systems which compete for similar resources, the narrative around marine ingredients is not there and a focus more on food-feed competition and "low opportunity cost" feedstuffs is more prevalent (Van Zanten *et al.*, 2018). Therefore, a discussion is necessary on which of the sustainability impacts is considered most important within the trade-offs. Certainly, marine ingredients supplies from forage fisheries cannot grow but there are many underutilised fisheries and aquaculture by-products that can add to the pool of raw materials available as highlighted within GAIN and previously by Jackson and Newton (2016) and Stevenson et al. (2018). Similarly, there are many terrestrial PAPs that are not well utilised in Europe. Both of these resources are low in environmental footprints (Figures 8.36, 8.38 and 8.40), costs to produce and have the added advantage of reducing waste through the value chain in circular economies. However, perception barriers need to be overcome for their mainstream use in Europe.

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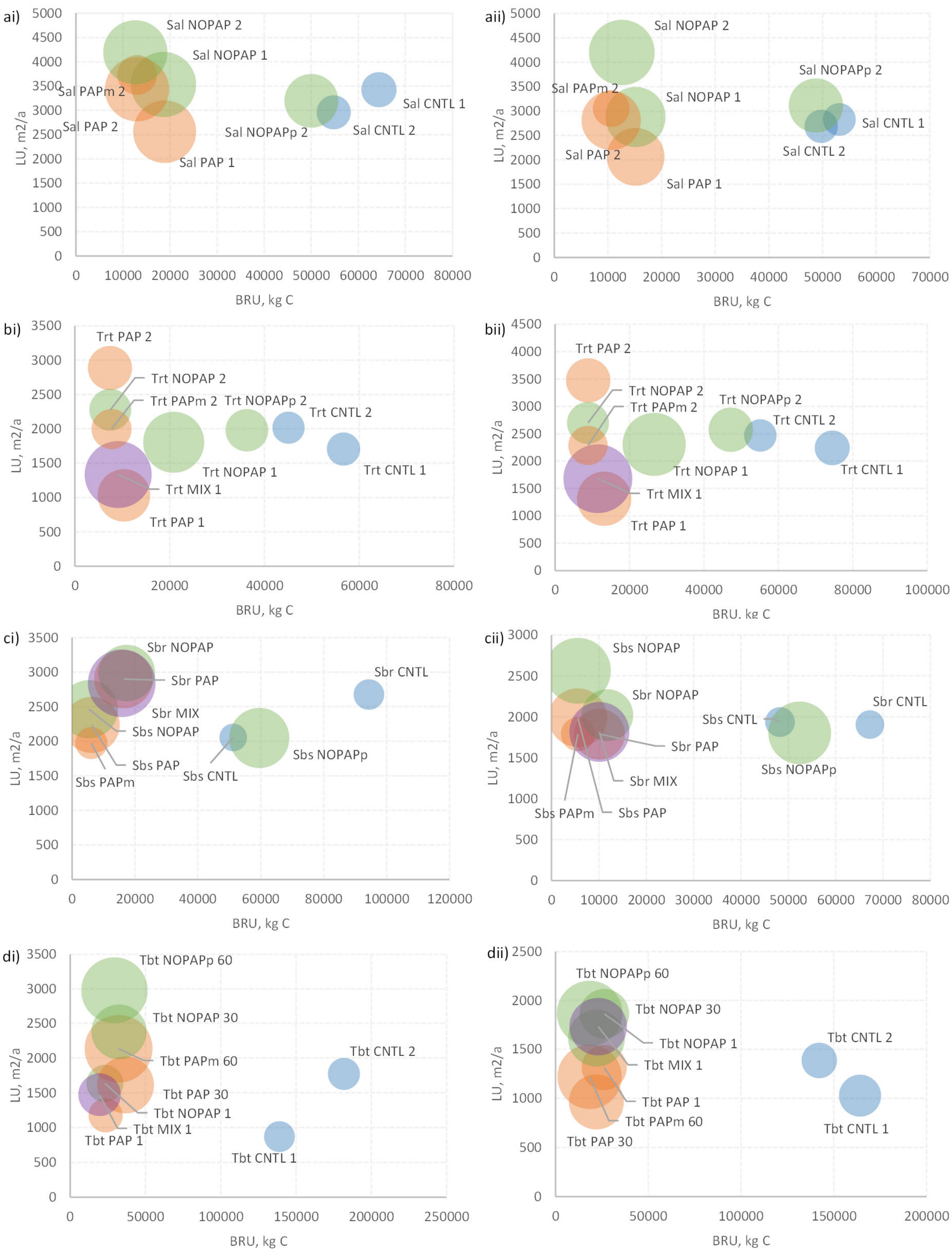

Figure 8.40 Biotic Resource Use, Land Use and relative GWP (bubble size) of GAIN nutrition trials for a) salmon, b) trout, c) seabass and sea bream and d) turbot, for i) one tonne of fish production and ii) one tonne of formulated diet.

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Regarding novel feed ingredients, many of the GWP impacts are related to direct energy use at the point of production (opposed to embodied impacts in the supply chain). Much of the impacts from GWP can therefore be avoided from highly energy intensive ingredients by producing them in countries with large quantities of renewables within their country energy mix. In this analysis, an EU average energy mix has been used which has much lower renewable energy contribution overall compared to Norway and this would clearly have an effect in reducing overall GWP emissions as can be seen in Figure 8.41. Single cell bacteria protein and microalgae oil were two of the ingredients with the highest GWP and energy demand (Figure 8.36). By producing those ingredients in Norway, the contribution to GWP from electricity supply is substantially reduced from 65% to 11% for microalgae and from 51% to 6% for single cell bacteria protein, representing an overall reduction in GWP of 60% and 47% respectively. However, both ingredients still have substantial contributions from substrate supply and/or direct emissions and even with efficient energy mixes and consequently have GWPs of around ten times those of marine ingredients (e.g. blue whiting meal 1990 kg CO_2eq/tonne), soybean (1220kg CO_2eq/tonne not including LUC) and poultry by-product meal (1270kg CO_2eq /tonne), and twenty times those of the best performing marine ingredients from by-products (e.g. herring BP meal 629kg, CO_2eq/tonne and mackerel BP oil 662kg, CO_2eq/tonne).

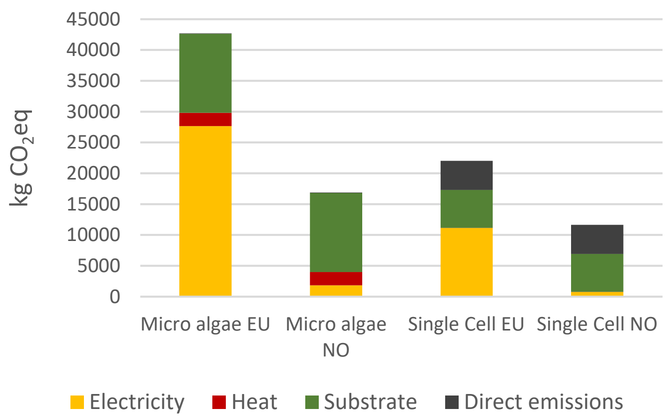

Figure 8.41 Comparative GWP impacts from single cell bacteria protein and microalgae oil produced with EU average electricity mix and Norwegian energy mix.

Despite macroalgae having very low environmental impacts in many key categories (Figure 8.38), it was only included at very low levels within any of the experimental diets as they are usually a functional component rather than providing a large contribution to animal nutrition (Wan *et al.*, 2019), Therefore they did not have large effect on the overall sustainability of any of the trial diets. Generally, macroalgae is low in protein, high in moisture, fibre and ash, with high seasonal variability (Wan et al 2019) which may limit their applications for feed purposes so that they may only be used in small quantities for functional purposes.

Section 9. Demonstration of the EISI index

There are a number of approaches that can be taken to combine individual indicators measured at individual producers into an overall assessment of the status of the industry. These may be, for example, an overall score on a 0-100 scale; the fraction that meets an agreed standard; or a more complex system in which different levels of a standard may be met by different parts of the industry.

A simple score has the drawback that it may suggest satisfactory average performance, when in fact parts of an industry fall far below an acceptable standard; it cannot distinguish between overall achievement of a standard from a mix of extremely high and low standards. In order to overcome the

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drawback of scoring systems, here we have employed a classification system that determines the fraction of the industry meeting a particular standard, with results being presented as traffic light graphs. This allows us to combine both the overall performance, and the mix of high and low standards; and further it gives a consistent way to present results for both individual indicators, and classes of indicator (Economic, Environmental, Social, and Welfare).

9.1 Methodology

The EISI was constructed for Norwegian salmon as a case-study because it had the most complete data set with large coverage of the industry. In the case of both carp and shellfish, there were not enough complete data sets and/or the number of respondents did not provide a large enough sample size to construct the number of indicators necessary for any meaningful index and subsequent analysis.

For each indicator within the salmon dataset, a set of threshold values representing different standards were selected. These were chosen to represent: excellent, acceptable, borderline, and poor performance. Values for these thresholds were selected by discussion within the research team, with regard to the actual range of observed values (as this indicated the feasible range of values the industry can currently attain), and with regard to values found in the literature from previous LCA studies, certification standard thresholds and other representative values of good practice. However, as the choice of values depended on the observed values in the models and the models were constructed after stakeholder consultation it was not possible to return to stakeholders for validation of these. (Values chosen for the thresholds can be found below in Table 9.1).

After establishing thresholds, we established the number of producers that fell into each category (poor, borderline, acceptable, excellent) for each indicator from the LCA and other collected data. For environmental indicators modelled in the LCA exercise this was generally the number of farm sites meeting each standard, but for other indicators (particularly economic) we could also incorporate the processors. For each indicator, the number of producers in each category was converted to the fraction of the industry. These rescaled values were then combined for all indicators in a class (economic, environmental, social, welfare) by weighing them using the mean stakeholder rating.

$$fraction\ meeting\ standard\ for\ class = \frac{\sum_{each\ indicator} indicator\ weight \times fraction\ meeting\ standard\ for\ indicator}{\sum_{each\ indicator} indicator\ weight}$$

Results are presented as bar graphs with a bar representing 100% subdivided into the fraction that meets each standard (poor, borderline, acceptable, excellent).

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Table 9.1 Data used in calculating EISI standards. The indicator ranges were established by reference to literature values and the range actually observed in the data (particularly when determining the best possible values that are already feasible). The number of producers are the data used to produce Figure 9.1; and the OVERALL rows show the values in Figure 9.2. For comparison, the industry mean is shown. In some cases, it can be observed that mean values of indicators mass a high prevalence of poor performance (where the mean lies in the borderline or acceptable category, but in fact the poor category is more common).

			Indicator range for each category					**Number of producers (or other level of observation) at each standard**			
Indicator	**units**	**stakeholder weight**	**poor**	borderline	**acceptable**	**excellent**	**industry mean**	**poor**	**borderline**	**acceptable**	**excellent**
Fish.rejection.at.processor	%	5.4	**>15%**	10 to 15	5 to 10	<5%	8	0	0	1	0
Feed.effeciency	ratio	7.7	**>1.5**	1.3 to 1.5	1.3 to 1.1	<1.1	1.21	0	2	6	0
Operating.cost FEED%	%	6.1	**<40**	40 to 50, >75	50-75%	55-65%	70.80%	0	3	5	0
Market.destination]	% exported	5.4		<20 >80	20 to 80	40 to 60	80.6	0	1	0	0
Fish.mortality.at.farm.(mass)	%	6.9	**>10**	5 to 10	3 to 5	<3	3.65	0	2	3	3
Diversity.of.products	number	5.2	**<3**	3 to 5	5 to 10	>10	11	0	0	0	1
Feed.efficiency	ratio	7.2	**>1.5**	1.3 to 1.5	1.1-1.3	<1.1	1.21	0	2	6	0
ECONOMIC OVERALL								0%	30%	52%	18%
Amount of production on electricity	%	6.2	<3	3 to 10	10 to 20	>20	20	4	2	0	1
Antibiotic.use	Number	4.3	>0	>0	>0	0	0	0	0	0	8
Water.quality.checks	%	5.4	<7	<15	15 to 50	>50	62	0	0	8	0
Benthic.impact	$g/m^2/yr$	6.4	>900	700-900	300-700	<300	1098	5	0	2	1
By-product.utilisation	%	7.2	<70	70	70 to 90	>90	80.35	0	0	1	0
Carbon.footprint.(GWP)	kg CO_2 eq	6.6	>3000	2500 to 3000	1800 to 2500	<1800	2599	0	4	4	0
CWU	m2	4.7	>2500	1500 to 2500	1000 to 1500	<1000	1811	0	0	8	0
AP	kg SO_2 eq	4.1	>40	30 to 40	20 to 30	<20	26.2	0	0	8	0
Eutrophication	kg PO_4--- eq	6.8	>120	100 to 120	80 to 100	<80	79.7	0	0	2	6
Land.footprint	m2a	4.2		>5000	<4000	<2000	3898	0	1	7	0
Energy.consumption - EROI	%	6.0	<.2	.2 to .3	.3 to .4	>.4	39.4	0	0	4	4

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FIFO	kg Fish In /kg	6.4	>1.3	1.1 to 1.3	0.9 - 1.1	<0.9	0.96	0	0	7	1
Impact.mitigation	average number	4.7		<2	2 to 3	>3	2.92	0	0	1	0
ENVIRONMENTAL OVERALL								10%	8%	62%	20%
Labour.structure gender	ratio	6.2	<0.25>3	<0.5>2	<0.66 >1.5	>1<1.5	1.03	8	0	1	0
Output.tonnes.per.employee	tonnes/person	5.6	<240	240 to 300	300 to 360	>360	376	2	0	1	5
Employee.safety.measures	check	7.3		<100	100	100	100	0	0	0	8
Certification	%	5.3		<20	20 to 60	>60	100	0	0	0	8
SOCIAL OVERALL								28%	0%	6%	66%
Emergency.harvests	%	4.7		>5%	0-5%	0	2.48	0	1	0	7
Farm.mortality.(number)	No. Fish per tonne	7.2	>120	100 to 120	80 to 100	80	105.8	3	2	2	2
Body.damage	%	6.3	<7	7 to 14	14-40	>40	18.5	4	0	1	3
Humane.slaughter	%	6.3		<95	95-100	100	100	0	0	0	1
Anti-predator.measures	%	5.0		<85	85-95	>95	100	0	0	0	8
Stocking.density	kg/m3	6.3	>35	25 to 35	10 to 25	<10	6.34	0	0	4	4
Welfare.training	%	7.3	<60	60 to 80	80-100	100	81	0	4	0	4
Health.management.plan	%	7.3		<90	90-100	100	100	0	0	0	8
WELFARE OVERALL								11%	12%	11%	66%

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9.2 Results

Results for the individual indicators can be seen in Figure 9.1. This indicates which particular indicators have some of the industry in the lowest 'poor' category, and also highlights divergence where some of the industry meets very high and others very low standards (e.g. Benthic impact is bimodal in this way, with few producers at an intermediate standard).

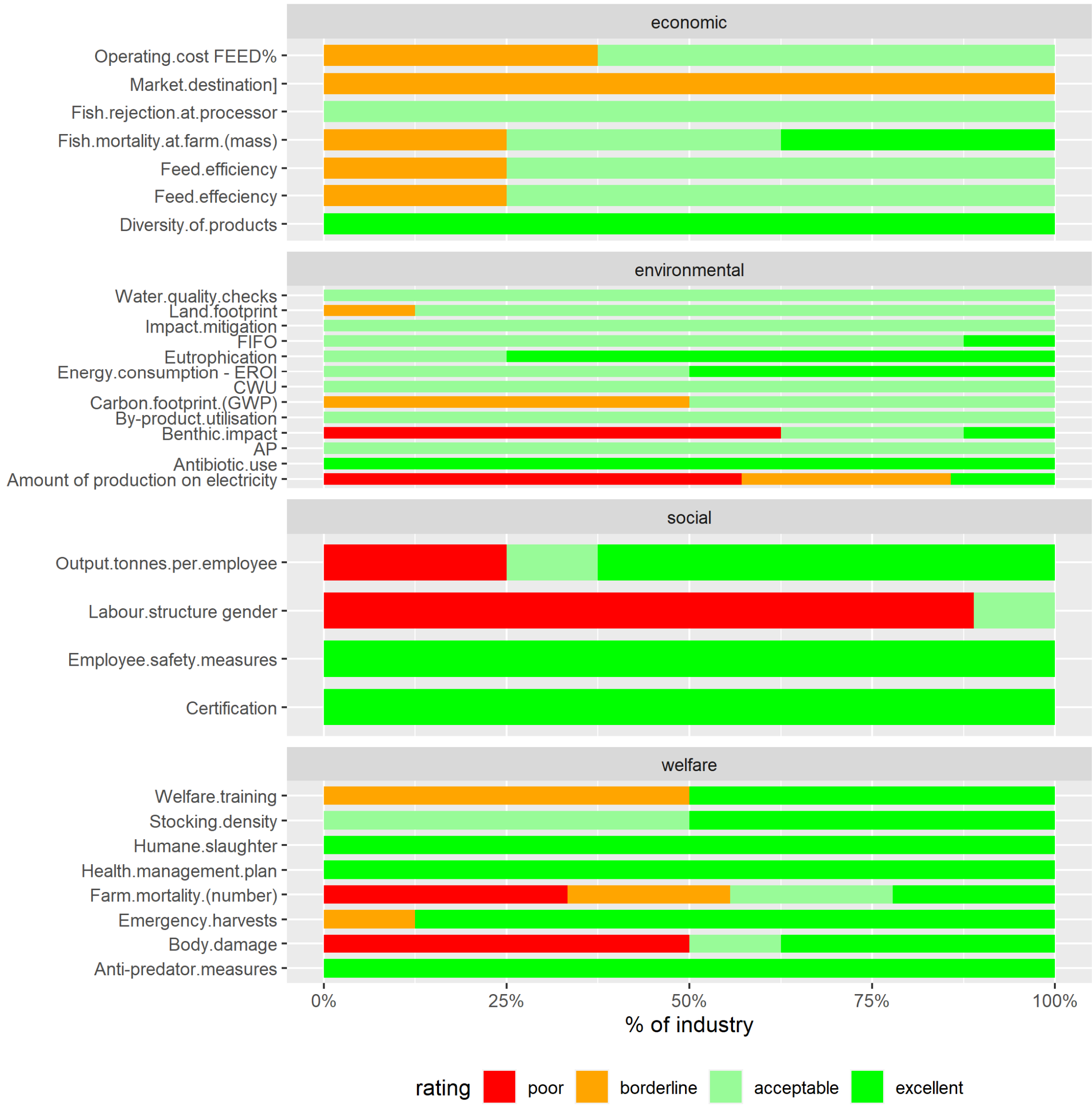

Figure 9.1 The fraction of the industry meeting different standards for individual indicators. See Table 9.1 for definitions of the standards and data.

Figure 9.1 shows that generally, salmon has acceptable or excellent standards of production, indicating a highly sustainable industry in many aspects. Key environmental indicators of FIFO and eutrophication are all acceptable or excellent. However, there are some areas of action such as benthic impact which was above the 700g/m^2/yr threshold cited by Gillibrand et al. (2002) in more

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than half the sites surveyed. Many respondents mentioned the transition to grid electrical power as a key sustainability issue, but few farms had more than 3% of their power derived from the grid. For social issues, mostly the industry performed well, although the gender balance was very male dominated at the farm sites. The indicator did not weight the numbers according to production as for the LCA results given in section 8, in which case the overall ratio is well balanced. This was because it was felt the indicator should reflect balance at each site rather than overall. One can debate the relative merits of the approaches and which may lead to the "best" outcome, which may depend on a host of other factors concerning pay, conditions, rights, equal opportunities and equitable outcomes that were beyond the scope of this index. Generally, the farm sites performed well on welfare issues but with a few sites having higher than acceptable mortality levels and around half performing too infrequent checks on the health status of their stock.

The weightings obtained from stakeholders were used to combine the individual indicators into an overall index in each category. Results of this are shown in Figure 9.2. The median performance (as a classification: poor, borderline, acceptable, or excellent) can be read of this graph at the 50% line. The total meeting an acceptable or excellent standard is the total of the two green categories in this graph.

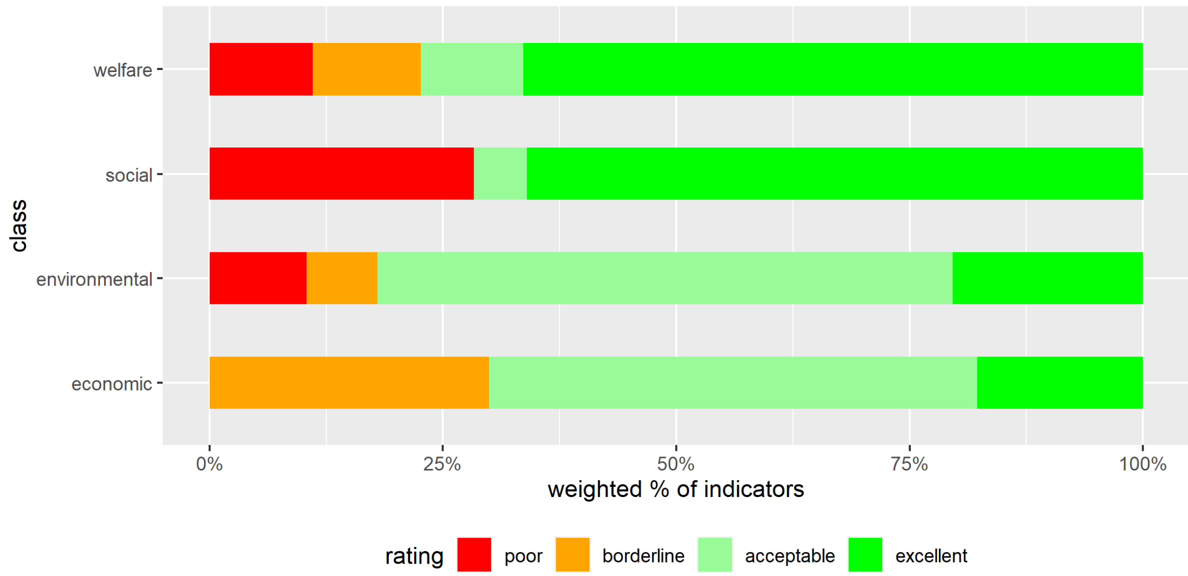

Figure 9.2 EISI indicator results for Norwegian salmon production

The results shown in Figure 9.2 show that the salmon industry performs well overall with medians in either the excellent or acceptable areas of the index for all four categories. However, there are quite a lot of extremes with around 10% to 25% of the industry rated as poor for welfare, environmental or social standards. Economic indicators appear to be less variable, with the bulk of the industry in the "acceptable" range and no poor performers as would be expected within a growing and well established industry.

The results here have been put together over a long process of data collection and stakeholder engagement, although through testing times of travel restrictions and there are a number of caveats attached to interpretation of such an index in its current form. The 'traffic light' scheme presents the economic and social indicators in a form that captures both the overall performance of the industry

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and the variation within the industry; and does so both for individual indicators and categories (economic, environmental, social, and welfare). However, the specific results have not been validated by stakeholders, and so the aim here is to consider the scheme of aggregating and presenting results rather than giving definitive conclusions.

9.3 Sources of variation and uncertainty

There are several important sources of variation that affect this interpretation of the indicators.

9.3.1 Sample size

The method is based on assigning each producer to a performance category. It is therefore subject to a high degree of sampling stochasticity when the number of producers included is small. Binomial confidence intervals could be used to formally assign confidence to the percentages, but for the sample sizes it is typically possible to include in an LCA, these are very wide (for example 4 out of 8 producers meeting an acceptable standard has a 95% confidence interval of 22-78%). A partial solution to this is to work with stakeholders to ensure that the sample is accepted as being as representative as possible; for example by assessing where some types of company may be over- or under-represented, and then adjusting the sample with additional data.

9.3.2 Thresholds

The choice of threshold is critical to the results, and a small change to threshold value can have a large effect on the number of producers placed in each category, especially when all producers have a similar performance. This has a particular impact when sample size is small and we recommend that when thresholds are set, the data and resulting categories are manually reviewed by stakeholders to ensure the thresholds are set at sensible levels. An alternative scheme to setting thresholds is to convert the measured indicator (e.g. global warming potential measured in kg CO_2eq) into a score in a fixed range (typically 0-100). However, there are two hazards to doing this. It still involves setting parameters for the function that converts the number to the 0 to 100 range , and there will typically be as many coefficients in the formula to do this as there are thresholds. Therefore, just as many (subjective) human decisions must be made as for setting thresholds. Secondly a single score does not represent the variability within the industry between good and poor performance.

9.3.3 Variation between stakeholder opinions

Here we have used the mean of all stakeholder weightings to combine the different indicators (i.e. in order to summarise the individual indicators in Figure 9.1 as the categories in Figure 9.2. Potentially the presentation of categories could differ substantially if different stakeholders weighted indicators differently. A confidence interval could be assigned to the final results by bootstrapping the process with a randomly sampled set of stakeholder ratings. A preliminary attempt at this suggested it had much less impact than either sampling variation or variation in choice of threshold, but there is insufficient data to assess this fully.

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9.4 Combinations and averages of indicators

This approach takes the view that each producer (or other unit of the industry) is assessed against a standard separately. This makes sense under two circumstances: (1) when any producer (e.g. a single farm site) has a local impact and must therefore meet the standards as it cannot be offset by better performance elsewhere; or (2) when we want to ensure parity in the industry, where all participants are held to the same standard, even where potentially one can offset another.
As an example, benthic impact has a local environmental impact, and excellent performance in one area cannot offset poor performance in another. The average benthic impact is therefore not relevant, only that all producers work towards meeting an acceptable standard. In contrast to this, climate change is a global phenomenon that depends on the total emissions and it is the average impact that matters.

9.5 Stakeholder validation

Any final published assessment of the environmental status of an industry would have to be evaluated by stakeholders before publication in order to ensure a consensus is met on: the threshold for acceptability in each indicator; the weighting of the indicator; whether the final results are considered to accurately reflect the status, or whether they suggest further iterations of adding data and stakeholder assessment (including reweighing and re-evaluating thresholds if new data suggests this is necessary). The work presented here demonstrates a possible method, but the actual threshold values used have not been assessed by stakeholders (although the weightings have).

9.6 The EISI as a benchmark

The intention of the EISI was to use it as a benchmark against which to test GAIN innovations. While this is possible on a superficial level, to test individual indicators, it is not possible to produce the entire EISI index for the innovations because no single innovation influences enough of the indicators apart from environmental indicators. For example, the social and many of the welfare indicators are not influenced in any way such as stocking density, gender ratio etc. However, the nutrition trials provide an excellent basis for comparing trade-offs withing environmental indicators, but extrapolating the results into the EISI is problematic for many. E.g. benthic impact was most influenced by the current rate and depth of the site rather than FCR, although that has an influence. The results of Section 8 demonstrate that for most of the experimental diets, the environmental indicators that are testable are significantly worse than for the control.

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Section 10. Implications for ecointensification

10.1 Assessment of EISI and cost-benefit results for novel feeds

10.1.1 Typical farm approach

Transferring the results and novel feed prices of the second feed trial block for seabream, salmon and trout to selected typical/example farms (see Kreiss and Brüning, 2020, D 4.1), confirmed the importance of a thorough economic cost-benefit analyses in addition to feed trials, besides environmental sustainability assessment and the evaluation of social acceptance of novel feeds. In general, novel feeds that were promising from a growth performance perspective (NOPAP feeds), were in most cases economically unfavourable. The only exception here was NOPAP30 turbot feed, which offered the opportunity to increase profits (+21%) as this diet is cheaper compared to the standard diet, but did not significantly effect growth performance in contrast to all other diets tested for this species. Although growth performance results for PAP feeds were least promising within salmon, seabass and trout feed trials, formulation costs are comparably low (especially for PAP-) and for these species novel feeds including livestock by-products were economically most promising. For turbot the picture was different, the unfavourable growth performance exceeded by far, potential benefits from cheaper formulation costs here.

10.1.2 Environmental performance results

For Atlantic salmon novel feed formulations, the results from the economic assessment are further complemented by the EISI indicator results and indications are that the same trend is likely to prevail for other species that were assessed for novel feed ingredient diets. When considering the global warming potential (including land use change), cumulative energy use, consumptive water use and biotic resource use of the novel diets compared to a standard control feed, PAP- feed is overall most promising. Emerging feed ingredients, which were included in higher volumes within the other novel feed types, often require higher energy demand (e.g. insect meal) and more abstracted water demand than plants, in addition to being often more costly than e.g. land animal protein sources. Therefore, especially PAP- salmon and trout feed might be promising from environmental and economic sustainability points of view. However, potential long-term impairments on animal welfare connected to lower growth performance as well as social acceptance of such fish fed with formulations containing land animal protein, should be taken into account as well. The latter might cause reluctance in some European markets (The Fish site, 2017), although this could also be the case for some of the emerging feed ingredients such as insect meal (Szendrö et al. 2020). In general, preferences for sustainable lifestyle and products is known to differ between age, education and location of stakeholders/consumers (Krause et al. 2020 D3.7; Maesano et al. 2020), which is also the case for the choice of fish feed (Szendrö et al. 2020).

The economic analysis provided by the Typical Farm approach and the environmental data from the LCA analysis and other EISI indicators complement each other in that although some of the novel feeds show some promising growth performance, they have many hurdles to overcome in terms of environmental and economic sustainability. The VCA analysis in D4.2 further complements these

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findings as many stakeholders were interested in the potential of novel feed ingredients but the costs were of concern. The environmental impacts of novel feed ingredients is often not well understood by the industry because of the narrow focus on marine ingredient substitution.

The performance of different PAP diets was promising although it appeared that there were some curious interaction effects. While there has been considerable focus on the development of novel feed ingredients to replace marine ingredients, there has been far less attention on the improved utilisation of PAPs and the implications for all industries involved from a circular economy perspective. Although legislation is relaxing regarding the use of PAPs in animal feed, including poultry proteins to pigs and vice versa, there is considerable public resistance to the move. Non-ruminant PAPs have been allowed in aquaculture diets since 2013 but have not been adopted due to retailer resistance linked to perceived public perceptions. Such resistance is likely to continue unless there is substantial effort to change perceptions regarding the safety of such resources and informing the public about the environmental benefits of such circular economy initiatives. There are considerable amounts of funding being made available from various commercial and government pots on the technical issues surrounding development of novel feed ingredients. Far less funding is available on the policy, logistical and acceptance hurdles for existing ingredients or raw materials such as by-products which are demonstrated to be lower in environmental footprints and perform well within commercial scenarios from experimental data and areas where their use are accepted and highly adopted such as in Chile (Pelletier et al. 2009). Stakeholder data from Norway (D4.2) showed that most believed that novel feed ingredient adoption would remain low because of their high cost and likely to be used in small inclusions for functional feeds. If this is the case, the long-term challenges of supplying sustainable feed ingredients will remain and there is a pressing need to push through the EU policy initiatives that allow the use of PAPs and other by-product resources with action to improve consumer acceptability and therefore adoption within the feeds sector.

10.2 Recommendations

10.2.1 Development of the EISI

The EISI approach allowed compilation of a large set of indicators into an accessible index. While there are some caveats around the development of the EISI around a limited sample size and level of stakeholder engagement, resulting from travel restrictions that imposed massive constraints on data collection, the approach is valuable. The EISI applied to the Norwegian salmon industry presents a good overview of the strengths and weaknesses of the industry, providing one of the most comprehensive and balanced approaches to measuring the sustainability of the industry so far. The EISI indicators demonstrated a much more holistic assessment of the feed trials than possible through a narrow focus on marine ingredients and even some LCA assessments and highlighted trade-offs that should be applied in real world scenarios. The 'Typical Farm Approach' (TFA) provides a nice complement to the EISI indicators where commercial data can be extremely sensitive and challenging to obtain. It is recommended that the EISI is further developed with more rigorous stakeholder and expert validation around a larger data set. The EISI provides an industry benchmark from multiple points within the supply chain, whereas GAIN innovations were tested over a narrow range of criteria, therefore better methods of integrating the EISI with industry innovation should be identified so it can

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be better used as a sustainability toolkit in trial/ test situations, including integration with other sustainability assessment methods such as TFA to be more inclusive.

10.2.1 Policy recommendations for novel feeds

An assessment should be made regarding the adoption of PAPs in EU aquaculture. The indications from the TFA and EISI work both demonstrate that PAP diets are more economic and environmentally beneficial than most of the novel feed ingredients under development. More effort is required to understand the barriers preventing their uptake and communicating the environmental benefits of circular economies and reduced waste to consumers. This does not preclude the continuing development of novel feed ingredients but more funding should be made available for communication and perception activities. In addition, it has been demonstrated that more sustainable marine ingredients can be obtained from fishery and aquaculture by-products so that policy incentives are required to ensure that there is no wastage of by-products from the sector. As well as better collection, storage and utilisation strategies, more efficient processing should also be encouraged with a move away from unprocessed product. Complementary to this, work from D3.1 highlighted shortcomings around the suitability of substrates for insect feed. The only LCA of a commercial level Black Soldier Fly facility (Smetana et al 2019) highlighted that over 30kg of feed grade substrate was used to produce 1kg of insect meal. The potential for utilisation of category 2 by-product wastes should be investigated as a matter of priority, including evidencing safety concerns, for the production of insect meals for aquaculture.

The most promising novel feed ingredient in terms of emissions was macroalgae biomass. However, none of the feed trials included large amounts of the ingredient as formulation targeted such ingredients for their functional roles rather than macro-nutrition. The feed trials should be conducted using incremental levels of inclusion in a matrix of a limited set of ingredients to better understand the interactions between them. This should be combined with a predetermined set of EISI indicators that are most relevant for assessing the possible effect at a commercial scale.

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Annex 1 Life Cycle Inventories of Novel Feed Ingredients

All electricity mixes were European average market mix and data were horizontally averaged according to Henriksson et al (2013) where multiple sources were used.

Black soldier fly larvae (BSFL). Source; Smetana et al (2019)

INPUTS		
Wheat middlings, kg	10747	
Wheat starch slurry, kg	10747	
DDGS, kg	10747	
Electricity, kWh	8276	
Heat (gas), MJ	28581	
Water, m^3	194.7	
OUTPUTS		**Allocation, %**
BSFL meal, kg	1000	26.6
BSFL fras, kg	3820	32.9
BSFL puree, kg	1440	38.2
BSFL lipid, kg	340	2.3
Wastewater treatment, m^3	227.7	-

Mealworm. Source; Thevenot et al (2018)

INPUTS		
Wheat bran, kg	3813	
Wheat flour, kg	1182	
Sunflower seed meal, kg	1868	
Sugar beet pulp, kg	763	
Elecrticity, kWh	13371	
Water, m3	33.2	
OUTPUTS		**Allocation, %**
Mealworm, meal, kg	1000	88.5
Mealworm fras, kg	900	-
Mealworm lipid, kg	308	11.5
Sludge, kg	2538	-

Microalgae (heterotrophic). Source Smetana et al (2017)

INPUTS		
Glucose, kg	2380	
Nitrogen fertiliser, kg	21	
Carbon dioxide, kg	28	
Electricity, kWh	16189	
Heat (gas), MJ	7736	
Water, m^3	42.7	
OUTPUTS		**Allocation, %**
Microalgae oil, kg	150	60
Microalgae biomass, kg	850	40

Methantrophic bacteria. Source; Abbadi et al (in press).

INPUTS		
Ammonia, kg	150	
Di ammonium phosphate, kg	35.1	
Natural gas, m^3	10.9	
Compressed air, m^3	591	
Electricity, kWh	8290	
Water, m^3	3	
OUTPUTS		**Allocation, %**
Methantrophic bacteria protein, kg	1000	100
Carbon dioxide, kg	2000	-

Single cell bacteria/ algae protein ((Smetana et al., 2017) et al 2017, (Jarvio et al., 2021) et al 2021, (Maiolo et al., 2020) et al 2020)

INPUTS		
Nitrogen fertiliser, kg	86.5	
Phosphate fertiliser, kg	214.3	
Carbon dioxide, kg	5903	
Electricity, kWh	26040	
Heat (gas), MJ	617	
OUTPUTS		**Allocation, %**
Single cell protein	1000	100
Carbon dioxide	4722	

Annex 2 Surveys

Life Cycle Analysis and Costing Survey for Norwegian Salmon Industry

All questions refer to last complete cycle unless otherwise stated

- Economy
- Environment
- Society
- Welfare

Section 1 - Correspondence details

Table 1.1 Correspondent details

Date		**Name**	
Position / job title			

Table 1.2 Company / site details

Company Name (+ Anonymous Code)							
Site Name							
Address							
Telephone		**GPS Coordinates**					
		East			North		
Email							

Table 1.3 Registration and Certification

Farming system	Cage
Year Farm Established	
Certification(s) **(e.g. Freedom foods, ASC, GGAP, BAP)**	
Do you plan to obtain additional certifications?	

Table 1.4 Farm size

Total farm water area (m^2)	
Area occupied by infrastructure (m^2) (e.g. cages, feed barges etc)	
Total on-shore land area (m^2)	

Table 1.5 Traceability

How is data stored/shared within the farm/company	1. No record keeping	
	2. Paperwork only	
	3. A (offline) computerised farm management system	
	4. Through a recognised certification scheme	
	5. Shared internal (cloud) system (option to share certain info with other companies/stakeholders)	
	6. A distributed and (decentralized) system/ledger, which is shared with other stakeholders along the supply chain (e.g. DLT, such as blockchain)	

Table 1.6 Transparency

What type of platform/strategy is being used to assure transparency to the consumer? (multiple answers possible)	1. We don't use any platform/strategy	
	2. Engagement with the (local) community (e.g. public events, fair)	
	3. Communicating CSR through investments or collaboration (sponsorship etc)	
	4. Company/product Website	
	5. Communicating CSR through certifications/standards	
	6. National advertising	
	7. Scheme linked to retailer transparency (e.g. QR codes linked to farm data)	

Section2 - Production details for last cycle

Table 2.1 Planning, stocking, harvesting

Farm maximum standing biomass (tonnes)					
	1	2	3	4	Cleaner fish
Date of Stocking					
Mean weight at stocking (per smolt)					
Number of smolts					
Mean smolt cost (specify unit)					
Maximum stocking density (kg/m^3)					
Date of Harvesting					
Mean weight at harvest (per fish)					
Total harvest weight (tonnes)					
Mean length per fish					
Average Price (NOK/ kg)					
Indicate if emergency harvest [Y/N]					
Emergency harvest reason					

Table 2.2 Sales

Name of processor	**Location**	**Quantity** (tonnes)	**Price** (NOK/tonne)	**Distance travelled 1***	**Transport mode 1** (e.g. Truck)	**Distance travelled 2***	**Transport mode 2** (e.g. well boat)

***Please states units (e.g. miles/km)**

Section 3 - Inputs

Table 3.1 Feed Inputs

Full commercial feed name	Weight (tonnes)	Wastage (%)	Cost (NOK /tonne)	Method delivered to site (e.g. boat/truck)
Total				

Table 3.2 Energy Sources

Energy Source	Total	Units	Total Cost (NOK)
Grid electricity			
Propane			
LPG			
Petrol			
Diesel			
2 stroke oil			
Kerosene			
Renewable: self-produced*			

*** Please, specify the type:** wind power/hydropower/solar energy/geothermal energy/bioenergy/electrical energy storage

Table 3.3 Energy Consumption Quantity

Consumption	Electricity	Propane	LPG	Petrol	Diesel	2 stroke
Generators						
Aerators						
Pumping						
Land vehicles						
Boats						
Barges (living unit)						
Incinerator						
Feed machines						

Table 3.4 Chemicals, disinfectants, therapeutants etc. in last cycle

Substance	Use*	Use Mode (e.g. in feed)	No. applications per year	Total quantity (specify units)	Total Cost (NOK)

*e.g. disinfectant, disease / parasite treatment, antifoulant etc

Section 4 – Infrastructure & Production inputs

Table 4.1 Cage details

Cage type (circle / square)	Manufacturer and model	Main materials	Individual Cage Dimensions (metres)*	Individual Cage Depth (metres)	Individual Cage Volume (m^3)	No. of cages	Expected life span (years)

***For circle enter circumference, for square enter surface area, i.e., length x width.**

Distance of cage site from land	**Miles [ ]** **Km [ ]**

Table 4.2 Automatic feed delivery

Feeder manufacturer	Model number / name	Capacity (feed/day)	Main materials	Wattage (kW)	Mains / generator/ barge?	Expected life span (years)

Table 4.3 Feed barges/silos/hoppers

Manufacturer	**Model number / name**	**Feeder type ***	**Main materials**	**Quantity**	**Distance from shore base**	**Expected life span** (years)

*feeder type (from table 3.3) associated with feed barge/silo/hoppers

Table 4.4 Other infrastructure

Other Components	**Manufacturer**	**Model** (if applicable)	**Main materials** (e.g. polyethylene)	**Quantity**	**Expected Life Span** (years)
Nets					
Piping					
Moorings					
Pumping systems					
Oxygenators					
Other*					

<u>Section 5. Cleaning and waste management</u>

Table 5.1 Net maintenance

	Location of activity (e.g. on farm / co. name etc)	**Distance from farm site**	**Chemicals used**	**Type of process/rig**	**Energy used, year/ appl.**	**Total Cost** (NOK /year)	**Treatments per year**
Net cleaning							
Antifouling application							
Anchors							
Ropes							
Chains							
Buoy							

	Number of divers	**Time per treatment**	**Treatments per year**	**Other equipment**	**Power, KW**	**KWh/ fuel L**	**Cost**
Divers							

Please briefly describe net cleaning and antifouling systems and procedures

Table 5.2 Section Recycling and disposal

Material	Disposal type	Location	Distance travelled*	Quantity	Total Cost
Cages					
Nets					
Feed bags					
Feed pipes					

***Please state units (km/miles)**

Section 6 - Water Management

Table 6.1 Physical characteristics

Mean current speed (m s^{-1} $year^{-1}$)	Mean Depth of sea	Mean Water Temperature

Table 6.2 Water Monitoring

	Parameter	Recording (real time/ daily/	Comment

Regular (min monthly) water monitoring		**weekly/ monthly)**	
	pH		
	DO		
	Jellyfish		
	Phytoplankton (TAB)		
	TAN		
	P		
	Temperature		
	Turbidity		
	Suspended solids		

Table 6.3 Impact monitoring

	Internal	Regulatory body
Number of environmental surveys in the cycle		

Table 6.4 Area Management Plans

No. of farm sites in area management plan	What aspects do area management plans control (tick all that apply)
	Production quantities [ ] Fallowing [ ] Chemical use [ ] Disease [ ] Other specify :

<u>Section 7. Losses and health management.</u>

Table 7.1 Losses, last cycle.

Loss cause	**Total kg**	**Total number**	**Disposal route** (e.g. onsite incineration / ensiling then landfill / sold to ______)	**Distance travelled***	**Disposal cost** (negative if sold)
Disease					
Parasites					
Escapes					
Predation					
Post antifouling					
Post vaccination					
Post other treatment					
Extreme weather					
Unsold stock					
Transfer					

Table 7.2 Active body damages (each year or per each farming cycle?)

Damaged part	**Type of check** (e.g. visual, fish samples)	**frequency**	Notes
Skin			
Gill			
Eye			
Snout			
Fin			

Table 7.3 Fish welfare checks

Person performing the check	**Type of check**	**Check frequency** (regular / only in case of anomalies)
Employees		
Vet		

* visual check by leaving the fish in the water /by handling the fish; sea-lice and other parasites counting; vaccinations; other treatments with chemicals, etc.

Table 7.4 Staff welfare training

Activity	**Staff trained (positions)**	**number**	**frequency**
Fish handling			
Feeding			
Health management			

Treatments			

Table 7.6 Predation prevention measures

Type of predation	Type of precaution

Section 8 - Operating costs during the last complete cycle

	Amount (NOK or %)	
Electricity		
Diesel		
Petrol		
Chemicals		
Labour		
Admin		
Rent		
Maintenance		
Feed		

Section 9 - Labour (during the last complete cycle)

Table 9.1 Labour structure (type of workers and related hours of work)

		Full time workers	Part time workers	Seasonal workers
Administrative	No of employees			
	Mean hrs/day			
	Total days			
Management	No of employees			
	Mean hrs/day			
	Total days			
Farm	No of employees			
	Mean hrs/day			
	Total days			

Table 9.2 Wage distribution of operation

	Administrative	Management	Farm
%			

Table 9.3 Employee risk & safety

Possible hazards	**Type of hazard** (substance, activity, etc.)	**Exposure frequency** (average no. of occurrences/year)	**Measures safeguarding against risks** (training)	**Measures safeguarding against risk** (equipment)
Chemical				
Physical				
Environmental				

Section 10 - Sustainability Perceptions

Table 10.1 What factors do you foresee that could positively or negatively affect your farms performance over the next 1-2 years?

	Sustainability Factor	**Overall Rank**	**Response**

Negative			
Positive			
Uncertain			

Section 11. Comments and clarifications

Production	
Feeding	
Other inputs	
Infrastructure	
Health and welfare	
Employment	

Fish processing plant LCA survey salmon for 2018

1. Survey and Interview details

Date		**Name**	
Position / job title			

Company Name (+ Anonymous Code)							
Site Name							
Address							
Telephone		GPS Coordinates					
		East			North		
Email							

Year Plant Established	
Certification(s) (e.g. Freedom foods, ASC etc)	
Do you plan to obtain additional certifications?	

	Total	Offices	1e process line	2e process line	VAU	Cold storage
Total plant area (m^2) (buildings)						
Area occupied by infrastructure (m^2)						
Total land area of factory (m^2)						

Table 1.5 Traceability

How is data stored/shared within the farm/company	1. No record keeping	
	2. Paperwork only	
	3. A (offline) computerised farm management system	
	4. Through a recognised certification scheme	
	5. Shared internal (cloud) system (option to share certain info with other companies/stakeholders)	
	6. A distributed and (decentralized) system/ledger, which is shared with other stakeholders along the supply chain (e.g. DLT, such as blockchain)	

Table 1.6 Transparency

What type of platform/strategy is being used to assure transparency to the consumer? (multiple answers possible)	1. We don't use any platform/strategy	
	2. Engagement with the (local) community (e.g. public events, fair)	
	3. Communicating CSR through investments or collaboration (sponsorship etc)	
	4. Company/product Website	
	5. Communicating CSR through certifications/standards	
	6. National advertising	
	7. Scheme linked to retailer transparency (e.g. QR codes linked to farm data)	

2. General information

2.1 What activities does this fish processing factory do?

Salmon product	Amount of raw product, tonnes	Amount of finished product, tonnes	Amount of sales revenue, NOK
Slaughter and bleeding			
Primary processing to produce whole/eviscerated salmon			
Secondary processing to produce fresh fillets			
Secondary processing to produce frozen fillets			
Secondary processing to produce value added products (pies, terrines, mousses etc)			
Smoking			
Other fish products (white fish, shellfish etc.)			
Buy and sell fresh fish/crustacean (as agent/trader)			
Other (specify)			

2.2 What percentage of your processed product went to…..?

Type of buyer	%	Quantity	Value
Other processor			
Local wholesaler			
Local retailer			
Local exporter			
other (specify)			

2.3 Slaughter method

Automated stun [ ]	Manual stun [ ]	Ice [ ]	Other (?) [ ]	None [ ]

3. Sales, production and supply

Table 3.1 Processing quality assurance

Criteria for selling to the fish processing plant	**Fish rejection** (yes or no)	**If the fish is rejected, state the relevance of the criterion** (high / medium /low)	**Frequency** (average no. /(%) of fish rejected/year)
Size			
Skin colour			
Flesh colour			
Flesh pH			
Damages			
Deformities			
Parasites			

3.2 What are the main supplies and destinations from processing (all main co-products; fillets, steaks, smoked, gravadlax etc?

Species	**Source**	**Size distribution**	**Quantity of final product**	**Destination (company and location)**	**Value**
Total					

3.3 What are the main by-products from processing? (if destination is disposal give negative value)

By-product	% yield (total)	Quantity	Value	Destination (type and location)	Distance
Total					

3.3 Do you store by-products before sale/disposal?

If yes please give details below of chemicals used and amounts

By-product	Volume stored	Storage method	Chemical/volume	Cost of method
Total				

4. Inputs

4.1 Energy Sources

Energy Source	Total	Total Cost	Remark
Grid electricity			
Propane/LPG			
Petrol			
Diesel			
Wood (smoking)			
Own renewable (type)			

4.2 Energy Consumption

Main energy use by quantities or %

Consumption	Electricity	Propane/LPG	Petrol	Diesel
Generators				
Refrigeration				
Freezers				
Pumps				
Process line				
Smokers				
Packing machines				
Vehicles (type)				

4.3 Water source and Storage, last year

	Total use	Cost
Main water source		
Secondary water source		
Water Storage Method		
Water use		
Freezers		
Washing product		
Staff washing		

4.4 What measures are there to reduce the impact from processing effluent? E.g. drain traps, catch baskets, water treatment, reduced water usage, staff training etc.

Measure	Description

4.5 Record keeping on water quality discharge

Parameter	NH3/4	NO2	NO3	PO4	BOD/COD	Suspended solids
Frequency						

5 Other inputs and costs

5.1 Inputs used to produce the processed fish and seafood reported in table 2.1 (ingredients and chemicals etc)

Item	Quantity, tonnes	Origin	Cost
Salt			
Sugar			
Chemicals (disinfectants etc)			
Total			

5.2 Packing

Material	Quantity	Cost
Total		

6. Labour (in year 2018)

		Full time labour	Part time labour
Administrative	No of employees (family + other)		
	Mean hrs/day		
	Total days		
Marketing	No of employees (family + other)		
	Mean hrs/day		
	Total days		
Production line processing	No of employees (family + other)		
	Mean hrs/day		
	Total days		
Wages and benefits %	Administration		
	Management		
	Production line		
	Total		

6.1 Staff safety training

Activity	**Staff trained (positions)**	**number**	**frequency**
Fish handling			
Heavy equipment			
HACCP			
Chemical use			
Hygiene			

6.2 Employee risk & safety equipment

Possible hazards	Type of hazard (substance, activity, etc.)	Exposure frequency (average no. of occurrences/year)	Measures safeguarding against risks (equipment)
Chemical			
Physical			
Environmental			

7. Operating costs

7.5 Total costs

	Amount, NOK or %	
Admin		
Rent		
Certification etc		
Depreciation		
Wages		
Training		
Raw material		
Energy		
Fuel		
Water		
Other inputs (?)		
Total operating		

9. Changes in last 5 years

Table 9.1 What factors have changed in the last 5 years

Issue	Change	Response?
Raw material		
Products		
Markets		
Labour		
Legislation		

9.1 Future changes

	Sustainability Issue	Overall Rank	Response
Negative			
Positive			
Uncertain			

10. *Visual observations after survey (General estimates):*

Building material in buildings (please tick) and take pictures:

Building type 1: ________m^2 use:______________ Est. Year built:____________ no.______

Building	Wood	Plywood	Stone	Concrete	Brick	Steel	Aluminium	Other (please type)
Floor:								
Interior walls:								
Exterior walls:								
Roof:								
Framing:								
Number of storeys:				Avg. window size: m^2				

Building type 2: ________m^2 use:______________ Est. Year built:____________ no.______

Building	Wood	Plywood	Stone	Concrete	Brick	Steel	Aluminium	Other (please type)
Floor:								
Interior walls:								
Exterior walls:								
Roof:								
Framing:								
Number of storeys:				Avg. window size: m^2				

Building type 3: ________m^2 use:______________ Est. Year built:____________ no.______

Building	Wood	Plywood	Stone	Concrete	Brick	Steel	Aluminium	Other (please type)
Floor:								
Interior walls:								
Exterior walls:								
Roof:								
Framing:								
Number of storeys:				Avg. window size: m^2				

Building type 4: ________m^2 use:______________ Est. Year built:____________ no.______

Building	Wood	Plywood	Stone	Concrete	Brick	Steel	Aluminium	Other (please type)
Floor:								
Interior walls:								
Exterior walls:								

Roof:								
Framing:								
Number of storeys:				Avg. window size:				m^2

Building type 5: ________m^2 use:_____________ Est. Year built:___________ no.______

Building	Wood	Plywood	Stone	Concrete	Brick	Steel	Aluminium	Other (please type)
Floor:								
Interior walls:								
Exterior walls:								
Roof:								
Framing:								
Number of storeys:				Avg. window size:				m^2

Feed mills

1. **What <u>type of ingredients (incl. processed raw materials)</u> did you use in the last complete year per tonne of feed? Separate for different feed types.**

Ingredient	**MT**	**Country Origin**	**Transportation method?**	**Water use (m3/MT)**	**Water loss (m3/MT)**	**Energy use***

*energy source and unit (…)

Total energy consumption

Type	Value	Unit	Source
Energy consumption			
Carbon emissions			
Water Withdrawal			
Waste generation			

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