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The dilemma of opportunity in developing a life cycle assessment of emerging aquaculture systems - a case study of a Eurasian perch (*Perca fluviatilis*) hatchery recirculating aquaculture system.

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1. Introduction

Globally, aquaculture is one of the fastest-growing food production systems in the world and has been for the last 30 years[1] [2]. This growth has been driven by consumer demand for seafood products and a reduction in the availability of wild stocks to satisfy this demand. Consumers in more recent times have become more adventurous with their spending, and they have started to expand their palates to fish species which would not have been typically available or consumed [3]. To accommodate this change in consumer demand and with the majority of capture fisheries at or above their maximum sustainable yield [4], aquaculture will have to meet the shortfall between supply and demand [5, 6]. Eurasian perch (*Perca fluviatilis*) has been identified as an aquaculture species which can contribute to supply and supplement wild stocks for niche markets such as European alpine regions (France, Germany, Italy & Switzerland) while reducing pressure on wild conspecifics [7].

Production of perch via aquaculture is limited to a small number of countries, and this number has declined since the beginning of the 2000s. Currently, production is carried out in France, the Czech Republic, the Russian Federation, Romania, Bulgaria, Denmark, Ireland, Italy, Kazakhstan, Latvia and Switzerland [8]. Farmed production between 2012 - 2016, was dominated by the Czech Republic and Switzerland with an average of 44.3% and 37%, respectively, of total perch aquaculture output. During the same period, perch capture fisheries produced an average of 30,645 tonnes per annum, significantly higher than aquacultures 449 tonnes (1.5% of total capture fisheries) [8]. Despite these differences in supply, capture fisheries are not currently able to meet demand [9].

Irish perch aquaculture production increased from 5 tonnes in 2008 to 45 tonnes in 2014 (FAO, 2018, BIM 2018), before decreasing to 15 tonnes in 2015 with commercial production ceasing shortly after. Currently, in Ireland, there is a perch hatchery and grow-out site in operation. These sites combined have a total licensed production capacity of 45 tonnes per annum (10 for the hatchery and 35 for the grow-out site). This is a joint venture between, Bord Iascaigh Mhara (BIM - the Irish seafood development state agency) and the peatland board, Bord na Móna (BnM).

The two sites differ from conventional facilities in that they comprise recirculating aquaculture multitrophic aquaculture pond systems (RAMPS)[2], also known as multitrophic recirculating aquaculture systems (MRAS). RAMPs consist of a split pond design, where fish are contained within

[1] It must be noted that this has been disputed in the recent literature [1. Edwards, P., et al., *Misunderstandings, myths and mantras in aquaculture: Its contribution to world food supplies has been systematically over reported.* Marine Policy, 2019. **106**: p. 103547.

[2] The hatchery site served as the pilot site of the RAMPS concept. The full-scale site has several differences to the pilot, but the concept and approach is very similar.

one section of the pond while the remaining part of the pond is dedicated to the treatment of the water by using algae and duckweed (*Lemna sp.*). This RAMPS concept uses an integrated multitrophic aquaculture approach (IMTA) whereby nature-based treatment of nutrients from fish production can result in a secondary product which can, for example, be used as biofuel, bioplastics or a functional feed ingredient [10].

With perch identified as a viable candidate for the diversification of freshwater aquaculture and this novel aquaculture system design selected as the means of culture, it is essential to assess the environmental performance of this species.

Life cycle assessment (LCA) is a biophysical accounting technique, which estimates the environmental burden of a product and its production system. It is an ISO technique, and the principals of its application are standardised within ISOs 14040 and 14044 (2006 a, b). An assessment can include all processes and systems of a product from the cradle to the grave, or it can assess the associated impacts under a narrower scope, such as cradle to farm-gate. Within LCA of aquaculture, the most common system boundaries used are cradle to farm-gate (CTF) [11]. For the most part, LCAs have been carried out on finfish, with salmonids receiving the greatest attention [11, 12].

To date, and to the best of the authors' knowledge, there have been no LCA studies of Eurasian perch production. The only available item looking at percid aquaculture comes from the grey literature, a report from a master's degree programme at the Swedish Royal Institute of Technology [13]. This report uses a functional unit of 1 kg of edible fillets (using a carcass yield of 40%) with the system boundaries set at cradle to processing gate. The authors of this report found that feed and electricity inputs were the dominating processes on the life cycle of this system. Similar results have been reported in other studies that have looked at other fish species produced in RAS [14-17]. There have also been very few articles published in the literature, which have presented the results or life cycle inventories of hatcheries, apart from two recent studies [16, 18]. As such, there is a dearth of information and studies on the hatchery stage of finfish production and particularly percids from a life cycle perspective.

As this sector and site are still being developed, a "dilemma of opportunity" is very much present [19]. This phrase refers to the dilemma of carrying out an LCA study to inform production processes, at the beginning or development of a product and it's systems or to wait until it is established and in full operation. The product development phase offers practitioners the greatest opportunity to inform the life cycle and reduce production-associated impacts. However, it is also the stage at which there is a limit on quantitative data. The inverse of this is true for later in the development cycle as there is an increase in the availability of data but a limit on the scope of a process intervention or decision on the environmental burden [19].

As such, this form of aquaculture is suffering from a dilemma of opportunity and is data deficient on several levels. In the case of this study, the deficiency is a result of the sites experimental nature as changes and improvements in husbandry, technology, feed efficiency and process controls are being made on a regular basis. Despite this dilemma, it is important to quantify and benchmark existing practices in order to identify processes or practices with disproportionate impacts.

To this end the objectives of this study were; (i) to benchmark production of 1 kg of perch at the hatchery gate, (ii) conduct the first life cycle assessment (LCA) study of perch production and (iii) to develop a methodology using an *ab initio* approach to generate an LCI for a data deficient RAS.

2. Materials and methods

2.1 Case-study site

The site comprised of a RAS perch hatchery and grow-out area (RAMPS) (Figure 1). The site has a license to produce 10 tonnes of perch per year and 200 kg of tench (not for consumption)[3]. Annual average production of perch is approximately 3 - 3.5 tonnes. The fish are transferred to a grow-out area for on-growing once they reach 5 g. For 75% of the stock produced, a typical cycle of the farm takes 24 months, with approximately 25% of the stock reaching transfer size in the first year. There are two stages of production on this site; (i) spawning and fingerling production. Where the fish are then placed in the grow-out ponds once they reach 5 g. This stage takes place over a 4-6-month period and (ii) on-site grow out in the ponds, which usually lasts from 6 - 18 months. Water within the ponds is recirculated via an airlift system, with supplementary aeration provided by paddle aerators or surge aerators.

This site is currently the only one of its kind in Ireland and possibly Europe. The site is experimental in design and forms the hatchery and pilot facility for what is expected to form the typical layout for future sites for perch production in Ireland. The RAS is typical of many other such systems, what makes this site unique is the species being cultured and the approach that is taken with the grow-out ponds. However, at this stage, it was not possible to include the RAMPS process within the LCA, due to the experimental nature of the site and ongoing research into the functions and dynamics associated with the algal and duckweed communities and processes.

2.1.1 Hatchery

The hatchery RAS consisted of twelve 670 L tanks, with water provided via a groundwater source. Water treatment is carried out via a drum filter, UV system and moving bed bioreactors (MBBR). Additional control of bacterial loading is maintained by the addition of peracetic acid twice daily per tank. There are typically four spawnings per year. The hatchery was prepared four weeks before eggs are placed in the system, with all associated services operating (lighting, water treatment, etc.) to allow for stabilisation of the system.

Following the hatching of the eggs, water use within this system per spawning event was 4.35 m^3, based on a water exchange rate of 25 L per day over two weeks, plus the initial makeup water. Once hatched, the larvae remain in this system for four weeks. During this period, the larvae consume their yolk sac and begin a diet of live feed. The live feed at the site was the brine shrimp, *Artemia sp*. The *Artemia* were hatched on-site, and their hatching and resource consumption on-site were accounted for in this study. Following the live feed, the batch were weaned onto dry feed. The dry feed had a high protein (57%) and lipid content (16%). The feed was given to the larvae as required. At this stage, there was also a high degree of wasted food, which the site operators estimated as averaging 20%. This waste was due to the operators enticing the larvae to take to the feed. Lost feed was captured in the drum filters of the system. Once the larvae reach an average weight of 0.2 g, they were transferred to the nursery section of the farm.

2.1.2 Nursery

[3]Note that tench production is not currently carried out and is a layover from previous production practices.

The nursery system consisted of 14 tanks ranging in volume from 2 – 4 m^3. The fish spend between 3 - 5 months in this system until they reach 5 g where they were transferred to the grow-out ponds. Water treatment in the nursery consisted of a similar arrangement to the hatchery, with the addition of oxygenation, ozonation, heat exchange, degassing columns and a larger drum filter. Additional treatment of the water was carried out with the use of sodium bicarbonate ($NaHCO_3$), to buffer pH and to provide salts to the fish. Supplementary aeration was provided by an air diffuser in each of the tanks. This section of the farm had a water exchange rate of 5% of the system volume per day. The water for the nursery was provided from a river adjacent to the farm. The water was gravity pumped into a mechanical filter, before being stored in a mesocosm prior to use in the nursery. Several feeds were given to the batches in the nursery, as there were a number of different grades of perch. Feed types used include floating or semi-floating feeds for larger fish. Constant grading was required to remove larger individuals who may have a predilection for cannibalism. These cannibals are generally two times the size of the average fish and were stocked in a separate tank.

2.1.3 Ponds

The grow-out area of the farm consisted of three ponds with a total volume of 1,151 m^3. The fish were corralled in one section of the pond, approximately 25% of the total volume, with the remaining 75% of the pond used for the treatment of the water by algae and bacteria. Aeration and water movement of the ponds was provided by an airlift system in each pond and backup surface aerators.

2.2 Life cycle inventory data generation

The availability of certain data necessary for the successful completion of a life cycle inventory was limited in several processes. In such cases it was necessary to generate the data using a base principle or *ab initio* approach.

2.2.1 Energy use

Energy use was based on the development of an inventory of each electrical device used in the production of 1 kg of perch at the farm gate. This approach was carried out by cataloguing each of the ratings on the devices and assuming that each was operating at its maximum stated wattage during the times of operation. Operation times for devices and systems were derived from on-site visits and interviews with site operators and staff.

2.2.2 Water use

Effluent and overflow from all the above systems (hatchery, nursery, ponds) were gravity fed to a primary settlement pond before moving through a surface flow constructed wetland and discharged to an adjacent stream via an overflow pipe.

<u>Hatchery</u> - Water use within the hatchery system was limited to the filling and draining of the system per batch of eggs and had a water exchange rate of 25 L per day.

<u>*Artemia*</u> - Within the *Artemia* cultivation system, 2,100 L of water was used per batch of larvae produced. Water was exchanged daily to maintain optimal conditions of the *Artemia* nauplii. Salt (NaCl) was used to optimise conditions for the emergence of *Artemia* nauplii.

<u>Nursery</u> - The water exchange rate for the nursery system was 5% of system volume per day. The total system capacity for the nursery was 80 m^3. The system was never kept at 100% capacity due to the requirement of space for grading and sorting of the stock. For the study period, January – October 2018, the system capacity utilisation rates were approximately 30% for January, 50% for February, 70% for March, and 80% for April, May, June and July.

<u>Ponds</u> - Water use within the ponds averaged 1% of the system volume per day. Depth profiles and the volume of the three external ponds (used to calculate water exchange rates in the ponds) were measured on-site.

2.2.3 Kerosene use

Gas oil or kerosene was used to heat the water within the hatchery, nursery and broodstock systems to maintain optimal growth and husbandry conditions. Records were not available as to the approximate usage per kilogram of perch produced at the site. An *ab initio* approach was taken to determine the amount of kerosene required to maintain these optimal conditions. Newton's law of cooling was used to calculate the energy requirements of heating the initial water for the system, exchanging water and the maintenance of the system (Equation 1). The target water temperature was 20°C; the amount of energy absorbed by the biomass in the system was also accounted for.

$$\frac{dQ}{dt} = hA(T_w - T_a) \qquad \textit{Equation 1}$$

Where *h*, defined as 20 W/m^2.K, is the convection heat transfer coefficient, *A* was the surface area (m^2), T_w was the target water temperature (°C), and T_a was the ambient temperature (°C). Boiler efficiency was estimated at 60% based on the lower limit of the acceptable range for most industrial boiler systems (SEAI, 2018). The amount of heat absorbed by the biomass to be in equilibrium with the water temperature was also accounted for based on the assumption that the specific heat capacity of animal tissue is 3,600 J/kg.K [20].

Monetary records were available for the purchase of kerosene during this period (volumes purchased were not on these documents). This allowed the use of the average price of heating oil in Ireland for 2018 (€ 0.7/l) [21] to estimate the volume used and in combination with the above equation and assumptions to allocate kerosene use based on biomass, growth and water use within the system.

2.2.4 Oxygen use

Oxygen generation was provided by a 3 kW compressor and a 0.12 kW oxygen generator that operated intermittently. Historical records for use were not available. Furthermore, the operator had identified several leaks in the system, which led to increased use of the unit. Thus, for this study oxygen generation and use was determined by calculating the expected oxygen consumption of the different weight classes of the stock in the hatchery and nursery as well as the oxygen demand for nitrification in the MBBRs. It was assumed that without the presence of leaks in the system, oxygen use would equal demand.

Oxygen consumption figures were based on results from Zakęś et al. [22] (as it was not possible to capture consumption data locally). Thus, the average oxygen consumption rate for hatchery and nursery were estimated at 300 mg O_2/kg/h for smaller weight classes/lower stocking densities and 203 mg O_2/kg/h for higher weights. The values outlined above, covered weight ranges of 18.5 - 56.5 g. Actual results for oxygen demand would be expected to be higher for smaller fish and lower values expected for larger fish, if site-specific data were available. There is a need for additional oxygen consumption datasets covering a wider range of weights for percid species.

The site operators aimed to maintain 100% oxygen saturation throughout the year. Oxygen use by the MBBRs was included in the analysis of oxygen use by allocating the necessary energy required to meet the demand of 100% nitrification of ammoniacal nitrogen. The theoretical oxygen demand for this was assumed as 4.34 kg of oxygen per kilogram of ammonia. Ammonia was estimated using a nutrient digestibility model [23, 24] (discussed further in 2.1.8).

Oxygen was delivered to the tanks using Point Four™ ceramic micro-bubble diffusers (Pentair Ltd., United States). The depth of the tanks was approximately 1 m, apart from the hatchery. Manufacturers' guidelines stated that oxygen transfer efficiencies were 40 – 50% in a tank with a depth of 1 m. Energy consumption was estimated based on Equation 2.

$$Energy\ use = \frac{SOUR}{SAE} \qquad Equation\ 2$$

Where SOUR is the standard oxygen uptake rate (kg O_2/h), and SAE is the standard aeration efficiency (kg O_2/kWh). The values given from this equation were in turn converted into kWh/kg biomass/h. There was a paucity in the level of information that could be gathered or collected as part of the MBBR and water treatment stages of this process. As such, the treatment process used only the information that the authors could stand over.

2.2.5 Nutrient emissions and treatment

Nutrient emissions were derived using a digestibility model [24, 25]. This methodology has been used widely in LCA of aquaculture systems [17, 26-31]. This approach allows the practitioner to calculate total nitrogen (TN), phosphorous (TP) and solids (TS) emitted as a function of feed input and the amount of each nutrient retained in the flesh of the fish. Other considerations of the approach include the amount of feed lost to the production system (non-ingested feed) and the apparent nutrient digestibility of a given feed. Within this model, apparent digestibility coefficients (ADCs) were used from the literature [24, 32]. The ADCs used in these calculations were taken from Papatryphon et al. (2004) and Strand et al. (2011) and were as follows: lipids 90%, protein 87%, carbohydrate 65%, fibre 0% and ash 50%.

Removal efficiencies for the RAS [33] and constructed wetland [34] were sourced from the literature and applied to the emissions from each of the systems (Table 1).

Table 1: *The removal efficiencies applied for each of the nutrient emission parameters derived from the digestibility model.*

Parameter	RAS [33]	Constructed Wetland [34]
TN	50%	35%
TP	76%	43%
TSS	85%	79%

2.2.6 Growth modelling

Fish growth was modelled throughout the production cycle using the thermal growth coefficient (TGC). [35]. The TGC is first calculated using the following equation (Equation 3):

$$TGC = \frac{(W_f^{\frac{1}{3}} - W_i^{\frac{1}{3}})}{\Sigma\,(T \cdot D) \cdot 1000} \qquad Equation\ 3$$

Where W_f is the final weight, W_i is the initial weight, T is the water temperature (°C), and D is the number of days. In order to arrive at a prediction of the final weight, the TGC must be used in the following equation (Equation 4):

$$Final\ weight = \left(W_i^{\frac{1}{3}} + \left(\frac{TGC}{1000} \cdot T \cdot D\right)\right)^3 \qquad Equation\ 4$$

The use of the TGC has been cautioned in several studies and papers [32, 36]. This caution arises from the assumptions which are required to allow the model to work [36]. This model requires the assumption that growth is steady and increases with temperature; that length is proportional to weight, and that length increases linearly over time [36]. However, this model and the temperature ranges used in this study have been found to be stable [32]. Given the available information and the stability of the model within this species and the temperature range of the site, the TGC was deemed an appropriate model to approximate the growth of each of the respective batches once they were mixed in the ponds.

2.3 Life Cycle Assessment

The LCA of this site was conducted in accordance with ISO 14040 and 14044 [37, 38]. There are four steps in any LCA (i) the definition of the goal and scope; (ii) the life cycle inventory analysis; (iii) the life cycle impact assessment and (iv) the interpretation of the results.

2.3.1 Goal and scope

The goal of this study was to benchmark and evaluate the environmental burden associated with the production of perch in Ireland and to overcome the dilemma of opportunity with the emerging system.

As perch production in Ireland is still at a trial phase, and it will be a number of years before there is sufficient data to characterise the end of life impacts such as processing, packaging, transportation, sale and use of the finished fillets - a cradle to farm-gate approach was selected. The boundaries of this study included all processes necessary to the production of perch, including raw material production, energy, water, oxygen, transportation and feed production (Figure 2). Transportation was given particular attention due to the reliance of Irish aquaculture on the importation and provision of necessary materials from outside Ireland and the European Union. The above processes are widely used in the literature and allow for ready comparison with production systems and species in other regions [17, 26-31, 39]. The functional unit of the study was 1 kg of live fish produced at the farm gate. Mass allocation was deemed the most appropriate choice in the context of this study. Economic allocation was excluded as the production process was not in steady state and there was notable variance in costs between batches. System expansion was not deemed suitable either as there are no readily comparable systems, products or processes similar enough to be displaced by perch. Given the above, allocation based on a physical approach was used [11, 37, 38].

2.3.2 Life cycle inventory (LCI)

Data were collected from farm records, questionnaires, interviews and on-site monitoring. Data relating to growth rates feed input and mortalities were collected from farm records. Data was not available for the production of the *Artemia* cysts; however, the processes associated with their use on-site and their transportation to the site were accounted. The composition of feeds and their ingredients were sourced from product packaging and compared against the information available on the producers' website (Table 2). Based on the region where the feed was produced, the closest likely source of each ingredient was used to estimate the transportation distances.

Table 2: *The material flow of the aquafeed used in the LCA models and the energy requirements for processing.*

Feed type		**Hatchery**	**Grow-out**	**Data sources**
Country of origin		**Japan**	**France**	
Inputs - Materials	**Units**			
Fishmeal	kg	200	330	Agri-footprint 4.0
Fish oil	kg	50	150	Agri-footprint 4.0
Wheat	kg	50	110	Agri-footprint 4.0
Yeast	kg	50	-	Ecoinvent 3.4
Triticale	kg	-	110	Agri-footprint 4.0
Soybean meal	kg	-	330	Agri-footprint 4.0
Krill meal[4]	kg	350	-	Agri-footprint 4.0
Squid meal[4]	kg	150	-	Agri-footprint 4.0
Potato starch	kg	50	-	Agri-footprint 4.0
Soy lecithin	kg	100	-	Agri-footprint 4.0
Energy[5]				
Diesel	kg	0.198	0.198	Ecoinvent 3.4
LPG	kg	1.17	1.17	Ecoinvent 3.4
Electricity	kWh	0.011	0.011	Ecoinvent 3.4
Heat	kWh	148	148	Ecoinvent 3.4
Outputs				
Aquafeed	kg	1000	1000	-

For background processes, such as fuel use, energy production and the packaging of feeds the LCI databases Ecoinvent and Agri-Footprint were used (Table S1 - 5). These databases were accessed through their own online portals or through SimaPro 8.5.0.0 [40]. LCIs were developed for three of the batches of eggs produced at the site in 2018 (A, B, C). Based on these three batches, an averaged LCI was also created (Table 3).

[4] Krill and squid meal were substituted in this LCI with fishmeal as this was determined to be the closet equivalent data available.
[5] Energy requirements for processing of the ingredients into aquafeed were assumed similar across all feeds. Data for feed processing was from Samuel-Fitwi et al. (2013).

Table 3: *The life cycle inventory of the production of 1 kg of perch to the farm gate. Batches A, B and C were analysed based on data completeness. Figures in brackets are the standard deviations of each of the respective inputs and outputs.*

Inventory data	Unit	A	B	C	Average per batch	Data Sources
Inputs						
Water	m^3	0.31	0.83	0.64	0.46 (±0.2)	Monitored
Feed	kg	1.16	1.61	1.83	1.53 (± 0.3)	Monitored
Energy	kWh	5.89	3.26	6.36	5.17 (± 1.7)	Monitored, modelled & ecoinvent 3.4
Kerosene	L	0.51	0.73	0.98	0.74 (± 0.2)	Monitored, modelled & ecoinvent 3.4
Outputs						
Total nitrogen	kg	0.04	0.05	0.05	0.05 (± 0.01)	Modelled
Total phosphorous	kg	0.01	0.03	0.02	0.03 (± 0.01)	Modelled
TSS	kg	0.24	0.29	0.33	0.29 (± 0.04)	Modelled
Fish	kg	1	1	1	1	-
Zootechnical information						
FCR		1.16	1.61	1.83	1.53 (± 0.3)	Monitored

Feeds for the farm had a considerable distance to travel. The *Artemia* cysts were transported to Ireland from San Francisco, USA via the Port of New Orleans. The hatchery high-protein dry feed was produced in Japan and shipped from the Port of Nagoya. The feed used in the ponds and nursery was produced in the North of France and shipped via Roscoff (Table 4).

Table 4*: The distances that each feed had to be transported in order to arrive at the farm. Routes were estimated using major commercial ports with connections to Europe or Ireland and validated against known freight routes.*

			Transportation type	
Feed Type	**Country**	**Units**	**Road**	**Ship**
Artemia cysts	Unites States	km	3,869	10,393
Dry larval feed	Japan	km	328	49,855
Grow-out feed	France	km	466	576

2.3.3 Life cycle impact assessment (LCIA)

The data gathered in the LCI were aggregated into the impact categories considered as part of this study and related back to the production of the functional unit. The LCIA methodology applied to the LCI was that of the CML baseline approach, as developed and updated by the Institute of Environmental Sciences, University of Leiden [43]. Eight impact categories were assessed as part of this study. The selected impact categories included those which allowed comparability with previous studies and also those which have the highest significance to aquaculture [12, 26-29, 31, 41, 42].

Global warming potential (GWP) was used. It is a measure of how much energy a gas will absorb over a time period, generally 100 years, and provides an estimate as to the emissions or contribution a process has on climate change. Measured in kg CO_2 equivalents (eq.) The GWP impact category assesses the impact of gases which absorb or inhibit infrared radiation, and which can increase the global warming effect. Acidification potential (AP) was used as it accounts for the acids emitted from a process to the atmosphere and their deposition in soils and waters. Measured in kg SO_2 eq. AP factors were applied as acidifying pollutants can have a substantial impact on freshwater systems. Eutrophication potential (EP) is a category which accounts for the impact in which a process may have on water quality, leading to excessive plant growth in freshwaters — measured in kg PO_4 eq. EP was considered as part of this analysis as compliance with the Water Framework Directive [44] is regarded as a matter of urgency within the aquaculture sector,_Cumulative energy demand (CED), accounts for the direct and indirect energy use throughout a products life cycle. It also accounts for the energy used in extraction, refining and manufacturing of a product used within the study products life cycle. It is expressed in MJ and focused on fossil and non-renewable fuels used for electricity generation. Water use (WU) was also applied as it accounts for the water footprint of a product. The AWARE method was used. It is measured in cubic metres (m^3). The AWARE method [45] is the recommended methodology for use in water-foot printing by the EU Joint Research Centre. Net primary production use (NPPU), is an impact category which is widely used in aquaculture LCAs to account for the biomass produced by photosynthesis which is made unavailable for other purposes [28]. It is measured using kilograms of carbon (kg C) and was first used in aquaculture LCA by Papatryphon et al., [46]. NPPU values were derived using the Supplementary Information of Le Féon et al,. [47]. This decision was made to allow for replication and also to adhere to the recent calls for standardisation of NPPU in LCAs [48]. Marine aquatic ecotoxicity potential (MAETP) and freshwater aquatic ecotoxicity potential (FAETP), are impact categories which estimates the emission of toxic substances from activities. Ecotoxicity potential is expressed as kg 1,4 dichlorobenzene eq (kg 1,4 DB eq.).

2.3.4 Sensitivity, scenario & uncertainty analysis

Sensitivity analysis was used to determine the impact or degree of change, which varying production inputs would exert on to the life cycle impact results.

The parameters which were tested for sensitivity included:

- If the site lowered the FCR to 1
- Reduce oxygen demand by 10% or 25%.
- Reduce electricity requirements by 10% or 25%.

As this LCA was an iterative process, these parameters were selected for sensitivity analysis after the LCIA as they proved to have the most considerable influence on the environmental impact of the production of 1 kg of perch at the farm gate. The parameters above are based on the targets that the operators hope to achieve as the production process and system become more stable and present optimal and realistic production scenarios.

Uncertainty analysis was conducted on the reference or baseline scenarios of each production system to determine the robustness and accuracy of the background and foreground data. This was carried out using Monte Carlo (MC) analysis with a large number of iterations (10,000 runs). MC simulation takes a random value based on the uncertainty of the data and calculates the LCA results based on this random value. This simulation is generally run between 1,000 and 10,000 times to produce an uncertainty distribution.

Uncertainty analysis was also carried out in the form of a comparative MC simulation (again 10,000 iterations). The results of such an analysis give a value of the percentage chance that a scenario or product performs better or worse than another does. The uncertainty analysis was conducted using the MC function in SimaPro 8.5.0 [40].

3. Results

The LCA of perch production focused on the culture of fry and juveniles in a RAS and their grow out in a pond system (RAMPS processes excluded). The culture of the fry in the RAS stage of the production cycle was based on three batches (A, B and C) from which an average impact was derived. Pond production was modelled as each batch left the RAS and began the grow-out stage. Growth was estimated using the TGC (Figure 3), with batches yielding an average of 343 kg at farm-gate from 1.9 kg of eggs over 153 days on site (Table 4).

When broken down across the different stages of production, the nursery phase had the most substantial contribution to the overall impact associated with 1 kg of perch at the farm gate. The nursery stage, in all impact categories assessed, accounted for greater than 60% of the burden. This was due to the high-energy and kerosene use. The contribution from the pond stage was due to feed use (EP) and production. The short time in the hatchery contributed relatively little to the overall burden, accounting for less than 1% of impacts across all categories. The average residency in the hatchery unit was 23 days. The residence time for fry in the nursery unit averaged at 62 days with the most prolonged stay being for B at 77 days and the shortest for C at 40 days. Time in the ponds was 67 days when averaged, but A spent 112 days in the ponds with B spending only 40 days outside the RASs. Despite the similar averaged times between the nursery and the ponds, the lower water exchange and lower energy inputs (electricity and heating) meant that the ponds stage of production had a lower impact than the nursery.

Table 4: *The biomass of each batch at the differing stages of production. The time in days each batch were resident on the site is also presented.*

	Nursery (kg)	Nursery (kg)	Pond (kg)	Culture duration (days)
A	0.[illegible]	70.7	406	210
B	3.9	360	516	138
C	1	125	106	110
Average	1.9	185	343	153

The results of the LCA for the three batches and the averaged production are presented in Table 5. Of the production batches, C consistently had the highest burden of all the batches (Figure 4). The only category which it did not dominate in was EP, where B was higher. The key contributing processes for GWP and AP in all batches were feed and electricity. Between the batches feed accounted for 34 – 53% of GWP. The bulk of feed related GWP was from the grow-out stage in the ponds. Electricity ranged from 36 – 58% of GWP and was generated during the hatchery and nursery stages. When averaged, the GWP for 1 kg of perch to the farm gate was estimated at 6.6 kg CO_2 eq. The average AP was 0.03 kg SO_2 eq./kg fish. Feed and electricity production were the primary contributors to this impact category. Between the batches there were changes in the hierarchy of AP contributors with electricity use higher in batch A. Heating oil also contributed an average of 14% of AP across the batches. EP was dominated by direct emissions from the RAS and RAMPS (89 – 95%). Feed production was the second highest contributor, with 5 - 9% of EP arising from this process. Averaged EP for 1 kg of perch was 0.03 kg PO_4 eq. The majority of EP arose from the pond stage of production

(58 – 87%), where water treatment was not as efficient as that in the RAS system. The average CED to produce a kilogram at this site was 117 MJ. Energy use was higher for on-site processes (pumps, lighting, water treatment) than any other process (40%). Heating oil was the second highest user of energy at an average of 35%. Feed production accounted for 20% of the CED for an averaged batch. Combined these three processes accounted for 95% of CED. Transportation and salt for *Artemia* production were relatively minor contributors with 2% of CED each. Water consumption was assessed using the AWARE [45] methodology which consider the amount of water in a region available, less the water needed by environmental systems and human activities. When averaged the water consumption per kg of fish was 1.49 m^3. The main contributor to this impact category was feed production at 43%, followed by fish production at 22% and electricity production at 20%. This methodology has not been widely applied in LCA of aquaculture to date, but these results do indicate very low water consumption for this system.

NPPU was only accounted for within feed production. Between the batches there was a coefficient of variance of 24%. Average NPPU per batch was 16.9 kg C. The majority of NPPU occurred in the nursery and grow out stages. With the hatchery only using 1.2% of average NPPU (0.2 kg C). NPPU derived from animal sources within the feeds were 75% for the hatchery and 48% for the nursery and growout feeds. This lead to the growout feed having 10.9 kg C/kg feed compared with the hatchery feed having a content of 10.6 kg C/kg feed. FAETP per batch was on average was 0.28 kg 1,4 DB eq. Feed production was the primary contributor to this impact at 93%. Heating had the second highest contribution at 4%, followed by electricity (2%) and transport (1%). MAETP had more diversity in the processes that contributed to its impact. Electricity production (for site use) accounted for 83% of the impact, with feed production at 6%. Salt use for *Artemia* production also contributed 6% of the impact, with heating oil use (4%) and transport (1%) making up the remaining 5%.

Table 5: *The environmental burden per 1 kg of perch to the farm gate for batches A, B, C and their average. Impacts and their percentage contributions per process are also presented.*

	Fish Production	Feed Production	Transport	Electricity	Heating	Salt (*Artemia* culture)	Total
GWP (kg CO_2 eq.)							
A	0 (0%)	1.93 (34%)	0.10 (2%)	3.29 (58%)	0.23 (4%)	0.11 (2%)	5.66 (100%)
B	0 (0%)	2.68 (53%)	0.13 (3%)	1.82 (36%)	0.33 (7%)	0.09 (2%)	5.05 (100%)
C	0 (0%)	4.19 (46%)	0.28 (3%)	3.71 (41%)	0.44 (5%)	0.40 (4%)	9.02 (100%)
Average	0 (0%)	2.94 (45%)	0.17 (3%)	2.94 (45%)	0.33 (5%)	0.20 (3%)	6.58 (100%)
AP (kg SO_2 eq.)							
A	0 (0%)	0.01 (31%)	0.00 (2%)	0.01 (52%)	0.00 (12%)	0.00 (3%)	0.02 (100%)
B	0 (0%)	0.01 (46%)	0.00 (4%)	0.01 (31%)	0.00 (18%)	0.00 (2%)	0.02 (100%)
C	0 (0%)	0.01 (41%)	0.00 (5%)	0.01 (35%)	0.01 (14%)	0.00 (6%)	0.04 (100%)
Average	0 (0%)	0.01 (39%)	0.00 (4%)	0.01 (39%)	0.00 (14%)	0.00 (4%)	0.03 (100%)
EP (kg PO_4 eq.)							
A	0.05 (90%)	0.00 (8%)	0.00 (0%)	0.00 (2%)	0.00 (0%)	0.00 (0%)	0.05 (100%)
B	0.11 (95%)	0.01 (5%)	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.00 (0%)	0.12 (100%)
C	0.08 (89%)	0.01 (9%)	0.00 (0%)	0.00 (1%)	0.00 (0%)	0.00 (0%)	0.09 (100%)
Average	0.08 (92%)	0.01 (7%)	0.00 (0%)	0.00 (1%)	0.00 (0%)	0.00 (0%)	0.09 (100%)
CED (MJ)							
A	0 (0%)	15.10 (15%)	1.51 (2%)	53.04 (53%)	28.49 (29%)	1.49 (1%)	99.63 (100%)
B	0 (0%)	20.94 (22%)	2.05 (2%)	29.36 (31%)	40.78 (43%)	1.14 (1%)	94.27 (100%)
C	0 (0%)	32.86 (21%)	4.27 (3%)	59.79 (38%)	54.75 (35%)	5.38 (3%)	157.04 (100%)
Average	0 (0%)	23.05 (20%)	2.55 (2%)	47.37 (40%)	41.34 (35%)	2.66 (2%)	116.97 (100%)
AWARE (m3)							
A	0.22 (20%)	0.43 (38%)	0.01 (0%)	0.34 (30%)	0.05 (5%)	0.07 (6%)	1.12 (100%)
B	0.59 (39%)	0.59 (39%)	0.01 (0%)	0.19 (12%)	0.08 (5%)	0.05 (4%)	1.51 (100%)
C	0.46 (22%)	0.92 (43%)	0.01 (1%)	0.38 (18%)	0.10 (5%)	0.26 (12%)	2.13 (100%)
Average	0.33 (22%)	0.65 (43%)	0.01 (1%)	0.30 (20%)	0.08 (5%)	0.13 (9%)	1.49 (100%)
NPPU (kg C)							
A	0 (0%)	12.64 (100%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	12.64 (100%)
B	0 (0%)	17.64 (100%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	17.64 (100%)
C	0 (0%)	20.31 (100%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	20.31 (100%)
Average	0 (0%)	16.85 (100%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	16.85 (100%)
FAETP (kg 1,4-DB eq.)							
A	0 (0%)	0.17 (92%)	0.00 (0%)	0.01 (4%)	0.01 (4%)	0.00 (0%)	0.19 (100%)
B	0 (0%)	0.24 (94%)	0.00 (0%)	0.00 (2%)	0.01 (4%)	0.00 (0%)	0.26 (100%)
C	0 (0%)	0.37 (94%)	0.00 (1%)	0.01 (2%)	0.01 (3%)	0.00 (1%)	0.40 (100%)
Average	0 (0%)	0.26 (93%)	0.00 (1%)	0.01 (2%)	0.01 (4%)	0.00 (0%)	0.28 (100%)
MAETP (kg 1,4-DB eq.)							
A	0 (0%)	64 (4%)	6 (0%)	1,547 (90%)	43 (3%)	60 (3%)	1,720 (100%)
B	0 (0%)	89 (8%)	8 (1%)	856 (81%)	62 (6%)	46 (4%)	1,061 (100%)
C	0 (0%)	139 (6%)	7 (1%)	1,744 (79%)	83 (4%)	216 (10%)	2,199 (100%)
Average	0 (0%)	98 (6%)	10 (1%)	1,381 (83%)	63 (4%)	107 (6%)	1,659 (100%)

3.2 Sensitivity, scenario and Monte Carlo analysis results

As stated previously, three variables were tested as part of the sensitivity analysis. When these inputs were varied, the most significant reductions in the overall burden per kilogram of perch at the farm gate was for an FCR of 1 (Table 6). The most significant reduction was seen in EP, at 42%. The second greatest reduction seen was in FAETP (41%) and NPPU (25%). The impact category, which had the lowest reduction was MAETP with a reduction of 3%, followed by CED at (9%). As electricity use was the highest contributor to MAETP, the scenario using 75% of the batch average had the greatest potential to reduce this impact.

Table 6: *The results of the sensitivity and scenarios considered to produce 1 kg of perch. The values outlined in the table are the percentages of the reference scenario where the reference is 100%. The FCR for the averaged production was 1.5*

Impact Category	FCR 1.0	90% Electricity	75% Electricity	90% O_2 Electricity	75% O_2 Electricity
GWP (kg CO2 eq.)	80%	96%	89%	98%	94%
AP (kg SO2 eq.)	82%	96%	90%	98%	95%
EP (kg PO4 eq.)	58%	99.9%	99.8%	99.9%	99.9%
CED (MJ)	91%	96%	90%	98%	95%
AWARE (m3)	81%	98%	95%	99%	97%
NPPU (kg C)	65%	100%	100%	100%	100%
FAETP (kg 1,4-DB eq.)	59%	99.8%	99.4%	99.9%	99.7%
MAETP (kg 1,4-DB eq.)	97%	92%	79%	96%	90%

In four of the five scenarios considered there was no great change in EP. This again demonstrates how the digestibility of feeds and their metabolic wastes dominate the EP of aquaculture production. A similar result was expected and returned for NPPU, as feed input did not alter in any other scenario.

Uncertainty analysis (95% confidence interval) of the reference scenario was conducted to test the accuracy of the data used in the back and foreground processes. The results of the simulation indicated that the results were robust, with low deviations (Table 7). The exception was water use, with a coefficient of variance of 255%, indicating that there was a very high degree of uncertainty within the background processes for water and these results could not be relied on to be representative.

Table 7: *The uncertainty results associated with the averaged production data.*

Impact Category	Mean	Median	SD	CV
GWP (kg CO_2 eq.)	6.6	6.6	0.3	4.1
AP (kg SO_2 eq.)	0.0	0.0	0.0	10.6
EP (kg PO_4 eq.)	0.09	0.09	0.00	3.99
CED (MJ)	117.2	116.2	11.9	10.1
AWARE (m^3)	1.6	1.8	4.0	254.6
NPPU (kg C)	16.9	17.6	3.9	23.1
FAETP (kg 1,4-DB eq.)	0.8	0.7	0.2	29.5
MAETP (kg 1,4-DB eq.)	2,722.2	2,606.9	669.3	24.6

A comparative uncertainty analysis was carried out on the average production data (X) and on the alternative scenario (Y), which would have the greatest opportunity in reducing the impact of production, i.e. FCR of 1. This was carried out using Monte Carlo analysis with 10,000 iterations (Figure 5). The results indicated that by reducing the FCR of the production there would be a significant chance of reducing the environmental burden across all impact categories. The only impact categories that showed a chance of the reference (X) performing better than the alternative (Y) were in water use, CED, FAETP and MAETP. That being stated, Y had a 1 – 35% chance of performing better in these impact categories than the reference. These results further support the dominance that feed and feed production have on the life cycle of carnivorous finfish production.

4. Discussion

Based on the above results, the objectives were achieved. However, in doing this, several data gaps, experimental design and improvement opportunities were identified.

4.1 Contribution to existing knowledge

To the knowledge of the authors, this is the first LCA of Eurasian perch (in the public domain). LCA of aquaculture has focused primarily on relatively few finfish species, such as salmonid species (Arctic char, Atlantic salmon, rainbow trout), sea bass, turbot and tilapia [15, 17, 26, 27, 29]. These species would be considered as being of regional importance given that approximately 90% of aquaculture produce originates in Asia where typically species such as catfish (*Pangasius sp.*) and cyprinids are produced [2, 49]. A limited number of studies have included the hatchery stage [16, 18, 29] in detail and no study has applied LCA to percid culture, RAMPS or a combination of RAS and RAMPS.

One of the critical outcomes of this study indicates that the factors, which influence the burden associated with the production of one kilogram of perch in Ireland, are (i) feed, (ii) energy and (iii) water. The results of this study indicate that the production of Eurasian perch in Ireland follows the trends of other carnivorous finfish species, which have been studied using LCA.

A difficulty in directly comparing the results of this study to others is that the majority of studies use a functional unit of one tonne of fish at the farm gate. Due to the nature of this site, the most appropriate functional unit was 1 kg at the farm gate and given economies of scale results from this study may not be linearly extrapolated to larger sites. However, given the demand and support which this species has, it is important to benchmark the process so that in future operators and practitioners can monitor their improvements and also generate and record data which eliminates or reduces the need for an *ab initio* approach such as the one applied in this study.

4.2 Comparison with other species and systems

LCAs of three freshwater aquaculture units were carried out on salmonid species as part of a wider research programme by the authors. The sites studied consisted of two flow-through (FT) salmon smolt units (Table 8). These studies originally had a functional unit of 1 tonne of fish at the farm gate but were reduced (through linear extrapolation) to 1 kg to allow for comparison.

Salmon have a large endogenous food supply and as a result do not require the transportation of live feed from the USA, as perch culture does. There are also questions regarding the lineage of the stocks cultured in each system. The salmon smolts most likely are the offspring of a process of careful selective breeding of strains, whereas the perch stock were cultured from wild (Irish) and farmed (Danish) conspecifics and only go back one or two generations. This selective breeding can increase feed efficiency [50], which may exaggerate the differences in the FCRs between these two species. The nature of the two systems also bears careful consideration given the inherent differences, i.e. FTSs low technology requirements versus RASs and their comparatively high technology requirements. This difference is further exacerbated with the inclusion of a pond grow out stage at the site. However, it is still important to see how this production system and product compare with the established systems and species.

A comparison of the abridged LCIs of the three sites (labelled Perch, Salmon-A and Salmon-B) showed that while perch had the lowest use of water of any of the systems studied, it did have higher requirements for electricity, heating and feed. Approximately half of the energy in the perch site was required for oxygen generation to maintain optimal growing conditions and to promote nitrification in the water treatment sections of the RAS. The amount of kerosene required to maintain a stable optimal temperature within the hatchery and nursery system was higher than the only other site to use it (Salmon – A).

The relatively short production time at the perch hatchery, (an egg to gate time of 152 days) means that the dataset may be skewed and that the FCR will lower as the stock grows and biomass of each batch increases. The FCRs of the salmonid LCAs are based on an annual figure given that egg to smolt production can take 9 – 12 months with a target weight of 100 g, which is almost double the period of growth for perch. Also given the role of the perch site, to produce fingerlings to 5 g, the use of FCR may not be crucial at this stage given that there is a higher degree of wastage during this early stage of production [51]. As perch do not have an endogenous supply of food when born as salmonids do, they have a higher FCR at this stage of production [7].

Table 8: *The abridged LCIs of each of the sites assessed as part of the EcoAqua project. Each of the sites has had their functional unit reduced to 1 kg of fish at the farm gate.*

Inputs	**Perch**	**Salmon - A**	**Salmon - B**
Water (m^3)	0.46	44.09	67.65
Energy (kWh)	5.17	2.01	1.92
Heating - kerosene (kg)	0.74	0.60	-
Feed (kg)	1.53	1.34	1.37
Outputs			
Total nitrogen (kg)	0.17	0.07	0.08
Total phosphorous (kg)	0.05	0.01	0.02
Total suspended solids (kg)	0.36	0.27	0.28
Fish (kg)	1	1	1

When comparing the LCIA results of the three sites, perch had the lowest water use (using the AWARE methodology) of all the sites (Table 9). Salmon – B had the highest of the three sites, with Salmon – A using approximately 35% less water than the other salmon site. AP for perch production is approximately a third higher than the salmon sites. The higher AP associated with the perch site when compared to the salmon sites was due to the use of nuclear energy in the grow-out feed and the dry larval feed used. The increased FCR for the perch sites increased the EP associated with the production of feed. The distances that feed had to travel for perch production (France, Japan, and the USA) were generally greater than the feed for salmon production (Scotland). This contributed to the higher CED of perch production. Nevertheless, the greatest contributors were electricity, kerosene and feed production, respectively.

GWP for the perch site was higher than the salmon sites. The higher use of energy, feed and heating all contributed to the GWP of perch production.

Table 9: *The LCIA results of the comparison with other freshwater aquaculture sites.*

Impact category	**Perch**	**Salmon - A**	**Salmon - B**
GWP (kg CO_2 eq.)	6.58	5.09	3.99
AP (kg SO_2 eq.)	0.03	0.02	0.02
EP (kg PO_4 eq.)	0.09	0.08	0.08
CED (MJ)	116.97	86.79	66.65
AWARE (m^3)	1.49	33.56	50.15

4.3 Accounting for reality

The choice of using the averaged data from the three batches of perch produced in 2018 included a batch, which lost almost 15% of the stock due to a mortality event. This event was very specific and was multifactorial (drought conditions, delays in companies receiving orders and inflexible licensing) and not very likely to be repeated. This was included as it was indicative of the reality of aquaculture production and of the experimental nature of this site.

This choice was tested by comparing the standard deviations and coefficients of variance (CoV) as to determine the variability and uncertainty associated with averaging the batches, that is an average based on two (A and B) or all three-batches. The CoV range for the average of the three batches was 22 – 106%, across all parameters. The greatest uncertainty with this averaged dataset was associated with the input of dry feed in the hatchery (106%), followed by Artemia input at 91%. When averaged, the CoV value for the three-batches was 44%. Using a two-batch average (A and B), the CoV range was 22 – 92%. Dry feed input in the hatchery again had the greatest CoV (92%) followed by energy at 73%. The CoV for Artemia inputs decreased from 91% to 17% for the two-batch average. The average CoV for the two-batch dataset (A and B) was 30%. Using a two-batch average would have reduced the uncertainty within the dataset, but again, given the experimental nature of the site, the three-batch average was used as it best represented reality.

A comparison of the LCIAs of the averaged datasets, using three batches and two batches showed that the reduction in the environmental burden would have been in the region of 2 - 21% lower for each category (Table 10). If the batch which lost 15% of the stock were excluded, the most considerable reduction would have been observed in FAETP and water consumption. EP had the lowest reduction, due to the FCR between the averages decreasing from 1.5 to 1.4. Even with the reductions in these burdens, there were still large standard deviations and CoVs with the dataset, highlighting the uncertainty and variance within the differing batches.

Table 10: *A comparison of the analysis of batches at two and three batch average.*

Impact category	3 batch (A, B, C)	2 batch (A, B)	% Reduction (2 batch analysis vs 3 batch)
GWP (kg CO_2 eq.)	6.58	5.30	19%
AP (kg SO_2 eq.)	0.03	0.02	19%
EP (kg PO_4 eq.)	0.090	0.088	2%
CED (MJ)	116.97	96.98	17%
AWARE (m^3)	1.49	1.18	21%
NPPU (kg C)	16.85	15.14	10%
FAETP (kg 1,4-DB eq.)	0.28	0.22	21%
MAETP (kg 1,4-DB eq.)	1,658.76	1,388.18	16%

4.4 Limitations and recommendations

The results detailed above form a baseline LCA, which can be compared against future results once the site has finalised its management practices and equipment. The farmed perch market is expected to grow in Ireland with several pilot studies and production scale farms under construction, allowing for a future comparison across production systems and management practices.

There are some limitations to this study. These limitations stem from the assumptions and models, which were used as part of the LCA. Given the approach used to model kerosene use for the farm, the input of kerosene for each batch of fish may be higher. This underestimation could arise from heat losses through grading and the drum filters, which were not accounted for. More accurate records of kerosene use, delivery and water losses would help to capture necessary data to reduce the scale of underestimation. Opportunities to make kerosene use more efficient could include implementing heat recovery. Such an intervention would allow for a reduction in the volumes of kerosene necessary to maintain adequate water temperature and the associated environmental burden with said volumes.

The operational energy demand of the RAS was similar between all the batches; however, the stocking densities and the survival rates varied significantly between batches. If the site operators were able to increase the stocking density within the system or increase the survival rate from egg to nursery-gate, the impacts per unit of production would decrease with higher biomass present. An example of this is how, the relatively low throughput at the site contributed to the higher GWP per kilogram at the farm gate when compared with Salmon A and B. Produce from a RAS system will inherently have a higher GWP due to the need for nitrification and organic matter oxidation (COD, BOD) in the MBBRs, as well as the oxygen generation for the fish. Higher throughput in the site would allow for a lower environmental burden per kilogram produced, but a balance between production capacity and environmental efficiency must be struck in order to realise this.

Site-specific data would have significantly informed the SOUR of each of the batches and their production stages, but it was not possible to conduct such a study at this site. There remains a significant gap in the literature on the oxygen demand of various weight classes of perch, which should be addressed. Like oxygen requirements of the stock, there is a pressing need for representative data from water treatment processes within the system, as the current study did not account for nuances in chemical and biological oxygen demand.

The site was assumed to achieve full nitrification of all process water. In reality, there may have been fluctuations in this value that would require a lower level of oxygen for successful nitrification and so a lower requirement of electricity. From the modelling approach used to estimate the required energy to meet the oxygen demand of the MBBR (based on an assumption of 100% nitrification), it was shown that the demand is not insignificant. When the energy required to generate oxygen for the stock and nitrification, per batch were combined, the requirements for nitrification could account for 34 – 49.6% of the total energy use.

With the above said, it has been demonstrated that using an *ab initio* or base principal approach that an LCA can be conducted on data deficient aquaculture systems and sites. The dilemma of opportunity is present at this natal stage of perch culture in Western Europe, but it was possible to identify what the dominant processes are and to provide a framework for the estimation of impacts per kilogram of fish to the farm-gate.

It is also worth noting that since the completion of this study there have been increases in production numbers at this site, with the same level of inputs (monetary and material), indicating that the system is nearing steady-state.

4.5 Life cycle considerations

NPPU has been widely used in aquaculture LCAs for almost 20 years and it does offer a means to account for impacts on primary productivity due to feed demand for aquaculture. Recent studies have reviewed its application in seafood LCAs and found that there is high diversity in its application [48]. In order to minimise this diversity the authors used the figures previously calculated by Le Féon et al. [47]. Further detail on this is available within the Supplementary Information (Table S6 - 7). An emerging means of assessing the impact of forage feed in aquaculture LCAs is that of the economic fish in fish out ratio (eFIFO) [52]. The eFIFO ratios were calculated for each batch of perch produced at the study site as per Kok et al., [52]. Batch A had the lowest eFIFO ratio at 2.0, followed by B at 2.8 and C with 3.2 (Table S8). When averaged, the eFIFO ratio for all batches was 2.7. These figures place the ratio at a similar level as that seen for other fed carnivorous finfish [52]. These figures are also higher than those for key Irish trout producers; whereby eFIFO ratio 1.7 has been observed [53].

These higher ratios for perch production can be expected to reduce as the system and process reaches steady state. Reductions in FCR will play a role in reducing eFIFO impact.

As aquaculture continues to grow, and the demand for aquafeed accompanies this growth, it is likely that proteins used in the composition of such feeds will come from multiple sources. The use of insect-derived proteins is a research area that is currently in development with a number of LCA studies published on the topic [54-58] and its influence on the life cycle costs of aquaculture produce [31, 47, 58, 59]. The use of insects to bio-convert food waste into valuable proteins, oils and fertilisers could enable the aquaculture sector to embrace the circular economy concept. Of the LCA studies which assessed insect meal as an ingredient in aquafeed, all observed an increase in EP and GWP when substituting for fishmeal. The origin of this increase lies in the feed for insect culture and energy for heat. The only area that saw a decrease across the studies was land use. The contribution of these to the life cycle impacts of insect production is expected to decrease as advances in technology and techniques become available. It is most likely that insect meal will become a key ingredient in aquafeed rather than a substitute for fishmeal as it can be low in several amino acids required by fish species [47, 54, 56]. Plant-based feeds have also been assessed in LCA of aquaculture [60-63]. The results of these studies generally show that the use of plant proteins such as soybean, rapeseed and camelina oil can reduce the impact across several impact categories. Another source of protein which has received recent attention as to its use as an ingredient in aquafeed is that of algae [64-68]. Currently, the use of algae as an ingredient in aquafeed is in a state of paucity from an LCA perspective and one that could be included in any future LCAs of this concept. With the above stated, the use of alternative feeds is not a panacea in the reduction of feed impacts in aquaculture [47, 59, 63, 69]. Each of the alternatives have their limitations and while it may reduce the degree of impact in some aspects, it can exacerbate the impact in others. For example, an increased use of plant ingredients in feeds can result in higher freshwater demand, land use and EP [70, 71]. A combination of the above alternative ingredients, utilisation of fish by-products and an LCA approach in feed formulation may help in reducing the environmental burden of this intrinsic process in finfish culture [70, 72].

Water use within this site was relatively low. The combination of RAS and RAMPS lead to high-water reuse and retention time on the site, indicating that water treatment within the RAS was operating well. The RAMPS operated well with treatment of nutrients by algae and duckweed being effective as evidenced by the low volumes of water turnover that were required. A high level of uncertainty was also found concerning the AWARE results. A CoV of 255% was returned by the MC analysis. Negative values were returned within the dataset, which indicates that in the uncertainty distribution, a process was treating seawater and returning it to freshwater. A high degree of uncertainty has been noted in several studies when using this methodology [73, 74]. In addition, another possible source of uncertainty with the methodology was that this study used the AWARE methodology version number 1.1.

The use of a RAMPS approach seems to offer several advantages to overcoming necessary environmental constraints and regulatory limits. The use of novel systems, like RAMPS, offers an alternative to the intensification of aquaculture. The treatment of nutrient-enriched waters to propagate plant and algal species which can be used as ingredients for feed, fuels and materials also open up additional revenue streams all while operators are complying with the emission limits set for them.

5. Conclusion

This study presents the first LCA of Eurasian perch production. The study provides a baseline analysis for a pilot site in Ireland for the year 2018 and indicates that the production of perch has similar impacts to other carnivorous finfish species in that feed is the dominant influencer on the environmental impact. The influence of electricity on the environmental burden of typical production is stronger than in traditional aquaculture systems, but the reduced volumes of water and areas of land per unit of production demonstrate the advantage of these systems (RAS and RAMPS) in comparison to FTS. With the Irish electrical grid due to become more reliant on renewable energies in the coming years the GWP associated with the production of 1 kg of perch at this site can be expected to decrease.

This study also outlined and presented a methodology, which can be applied to data deficient aquaculture systems and sites for established and emerging species using a basic approach. The dilemma of opportunity is something that is often a limiting factor when applying LCA or an eco-design approach to an emerging product or system. This study and its approach demonstrated that even when relying on an *ab initio* approach that it is possible to identify hotspots and intervention opportunities early in the design, which can reduce the burden of the system.

While the processes and dynamics of the RAMPS section of the system could not be included within this LCA, there is room for further studies with a greater scope such as cradle to market or grave and the investigation of co-products and the valorisation of classical waste streams from this system.

Acknowledgements

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The authors declare that they have no conflict of interest.

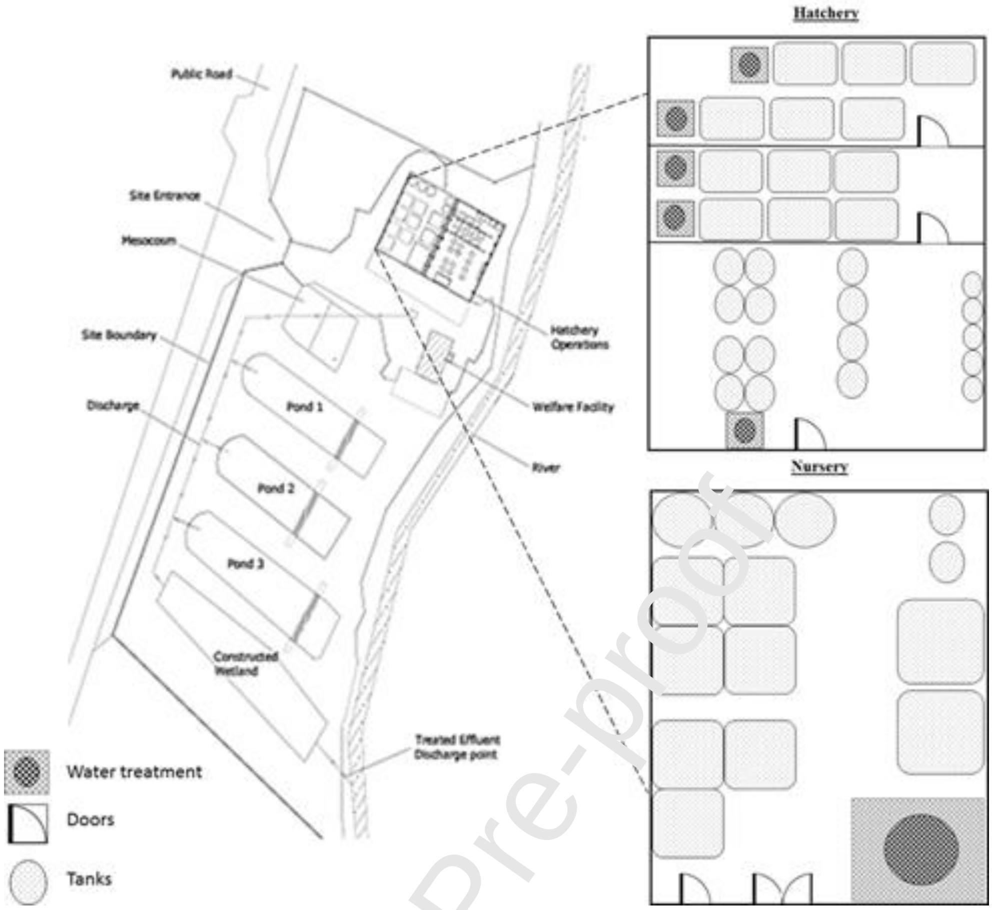

Figure 1: *The layout of the site. The hatchery, broodstock and nursery units are located in the buildings in the top right of the image.*

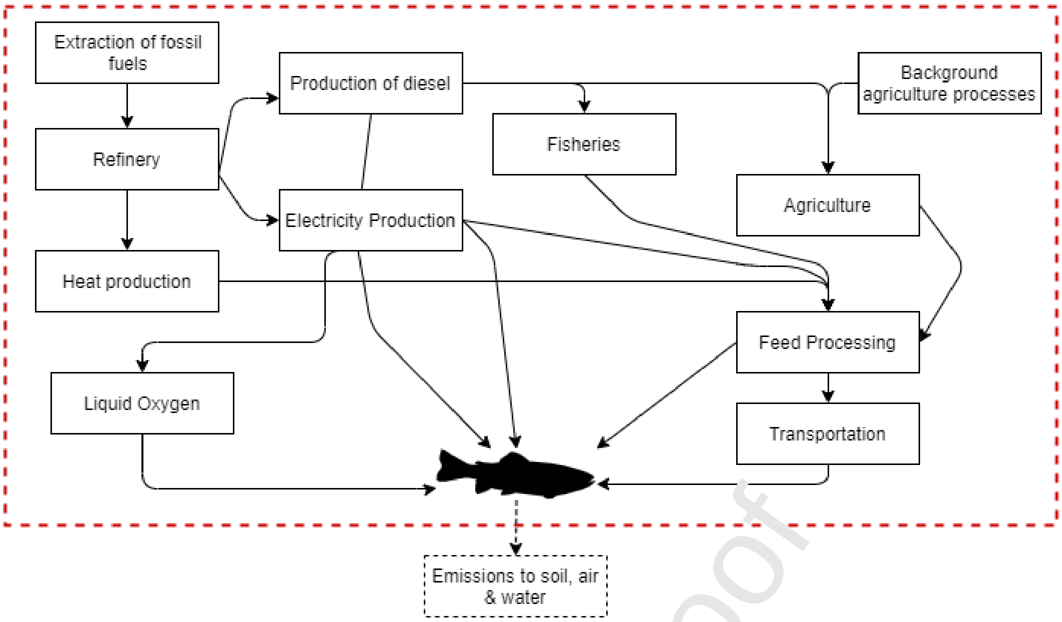

Figure 2: *The system boundaries and the processes considered as part of this study*

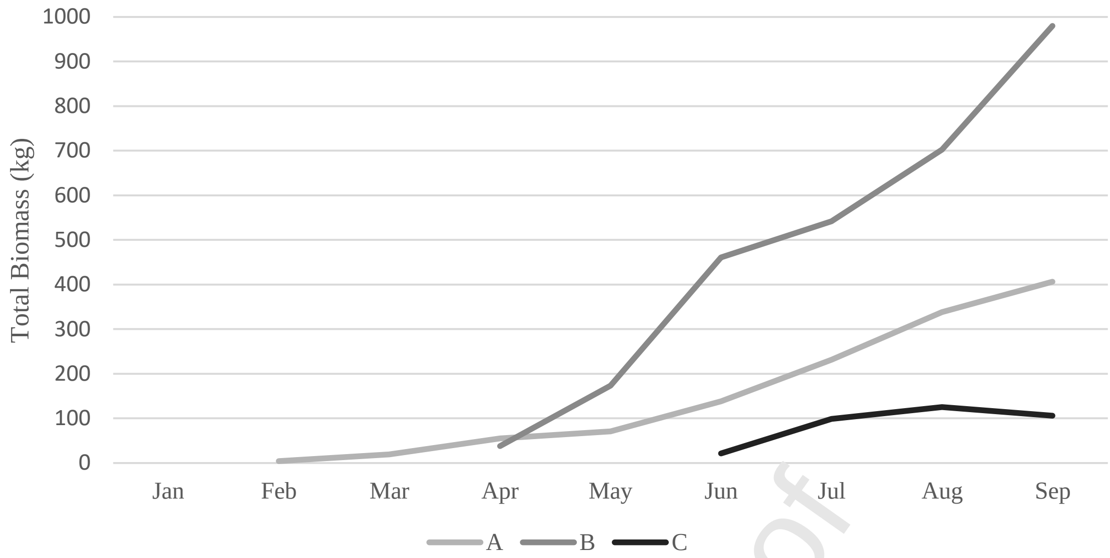

Figure 3: *The modelled growth (in total biomass) for batches A, B, and C. The decrease in growth for C from August to September was due to a delay in a customer being able to receive stock leading to overstocking on the farm and mortality events.*

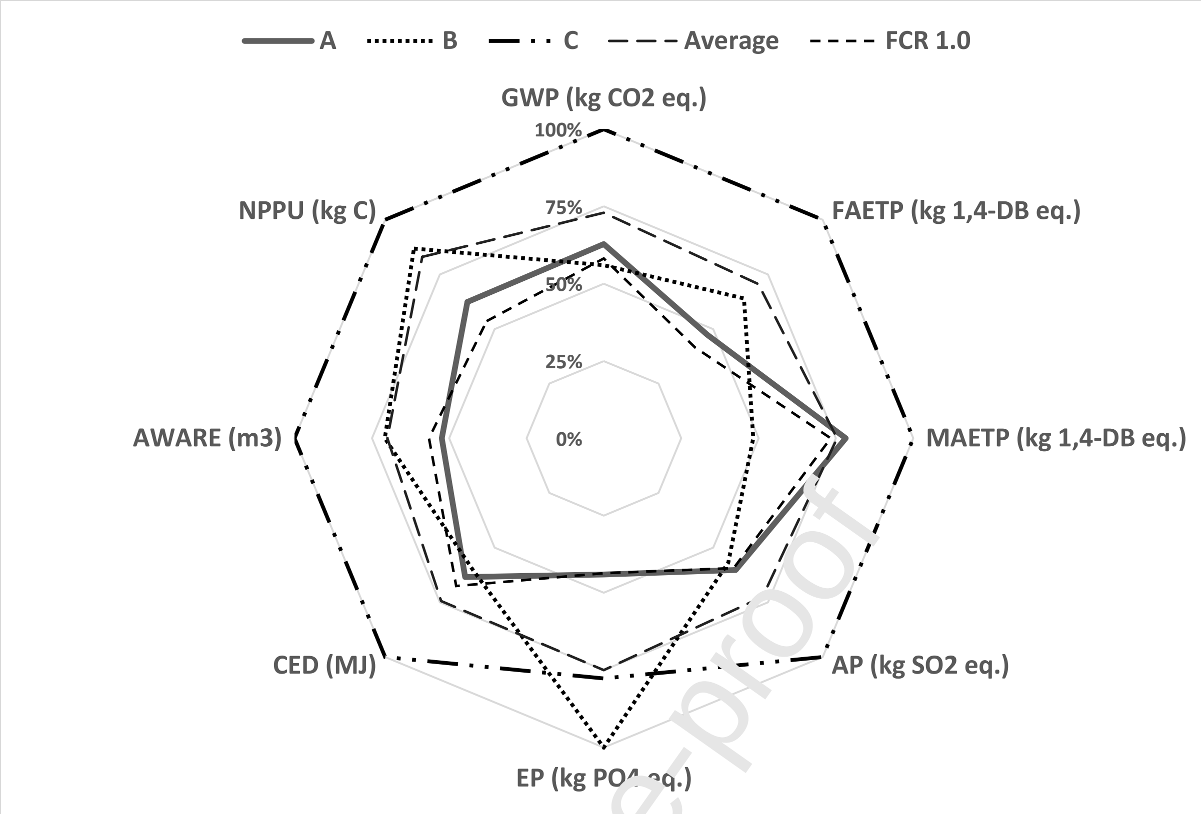

Figure 4: *The relative impact of each of the batches, their average on the impact categories considered. The scenario where the FCR is 1.0 per batch is also presented.*

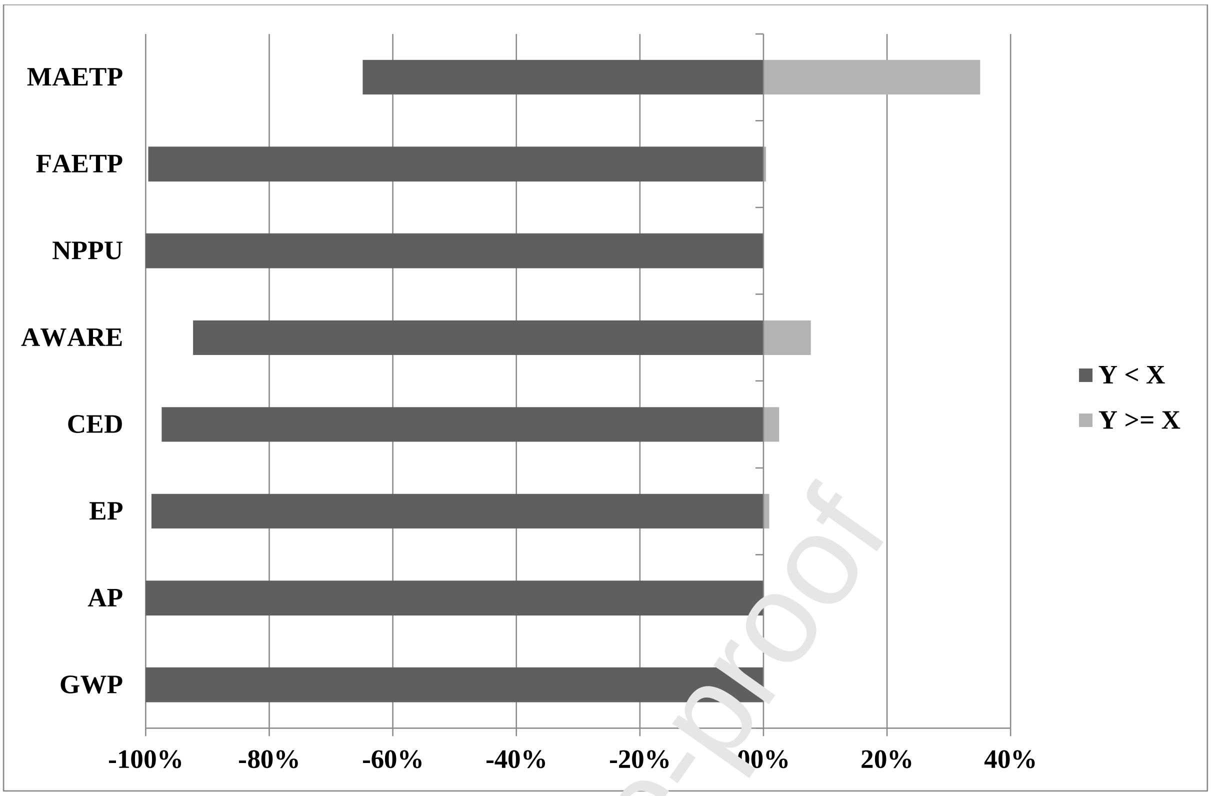

***Figure 5**: Results of a comparative Monte Carlo analysis between the average of the three batches (X) and the dataset adjusted for an FCR of 1 (Y). The x-axis shows the percentage of chance where there is a difference between the reference and the alternative scenario*

Ronan Cooney: Conceptualisation, Methodology, Writing – Original Draft **Alexandre Tahar:** Validation, Investigation, Writing – Review & Editing **Alan Kennedy:** Validation, Project administration, Writing – Review & Editing **Eoghan Clifford:** Funding acquisition, Supervision, Writing – Review & Editing

- First application of LCA to Eurasian Perch culture
- First LCA of RAS production in Ireland
- Provides a framework for overcoming the dilemma of opportunity in emergin aquaculture systems
- Considers five impacts of perch production on the environment.