Check for updates

DOI: 10.1111/jiec.13118

RESEARCH AND ANALYSIS

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

Quantifying environmental impacts of cleaner fish used as sea lice treatments in salmon aquaculture with life cycle assessment

Gaspard Philis[1] | Friederike Ziegler[2] | Mona Dverdal Jansen[3] | Lars Christian Gansel[1] | Sara Hornborg[2] | Grete Hansen Aas[1] | Anne Stene[1]

[1] Department of Biological Sciences, Norwegian University of Science and Technology, Ålesund, Norway

[2] Department Agrifood and Bioscience, RISE Research Institutes of Sweden, Göteborg, Sweden

[3] Section for Epidemiology, Norwegian Veterinary Institute, Oslo, Norway

Correspondence
Gaspard Philis, Department of Biological Sciences, Norwegian University of Science and Technology, Larsgårdsvegen 2, 6009 Ålesund, Norway.
Email: gaspard.philis@ntnu.no

Editor Managing Review: Robert Parker

Funding information
NTNU Sustainability; Swedish Research Council FORMAS, Grant/Award Number: 2016-00455

Abstract

Increasing pressure of sea lice, development of multi-resistance to chemotherapeutants, and alternative delousing strategies have been raising concerns about the environmental impacts of salmon farming. Ectoparasitic sea lice and its treatments represent a major bottleneck for the development of the Norwegian salmonid aquaculture. The environmental impacts of different treatments and their contribution to the salmon footprint remain unknown; these processes have been excluded from life cycle assessment (LCA) of farmed salmon. In this work, we apply LCA to quantify the impacts of three different value chains expressed per ton of cleaner fish farmed/fished, distributed, and used. The impacts of farmed lumpfish, farmed wrasse, and fished wrasse are then combined to calculate the footprint of the Norwegian biological lice treatment mix, expressed per ton of salmon produced. We found that wrasse fishing generates considerably lower impacts than farmed lumpfish and, a fortiori, farmed wrasse. The direct comparison of these value chains is compromised since LCA is unable to quantify ecosystem impacts and because cleaner fish delousing efficiencies remain unknown. Overall, the impacts of biological lice treatments have a low contribution to the salmon footprint, suggesting that using this treatment type could be a sound approach to treat salmon. However, such favorable results depend on three critical factors: (1) the efficiency of biological lice treatments needs to be confirmed and quantified; (2) ecosystem impacts should be accounted for; and (3) cleaner fish welfare issues must be addressed. This article met the requirements for a gold-gold *JIE* data openness badge described at http://jie.click/badges.

KEYWORDS
cleaner fish, industrial ecology, lice treatment, life cycle assessment (LCA), salmon aquaculture, sea lice

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
© 2021 The Authors. *Journal of Industrial Ecology* published by Wiley Periodicals LLC on behalf of Yale University

1 INTRODUCTION

It is essential to improve the sustainability of current food production and promote low-impact products to feed a growing population within the planetary boundaries (Conijn et al., 2018; Springmann et al., 2018). Ocean food production will be important for future food sustainability and security, but there are challenges (Costello et al., 2019). One example is the Norwegian salmon industry, aiming to increase production while respecting ambitious sustainability criteria (Meld.St.16, 2014–2015). The stagnation of production volumes reflects the severe biological conditions Norwegian farmers have been facing in recent years (Taranger et al., 2014). This is the result of intensive production of salmonids in net-pens, favoring the spread of infectious disease and parasites. Outbreaks of pancreas disease are frequent since this virus is endemic and widespread in Norway (Jansen et al., 2017). Infectious salmon anemia is also problematic, triggering isolation, and early slaughter since no vaccine or effective treatments are currently available (Hjeltnes et al., 2019). Stagnation of production is primarily due to the ectoparasitic sea lice *Lepeophtheirus salmonis* and *Caligus elongatus* and the required treatments to keep lice levels under control (Abolofia et al., 2017). Today, Norway enforces a strict lice treatment policy to protect its populations of wild salmonids, and farmers must perform delousing treatments if concentrations exceed 0.5 female lice (0.2 in the spring when juvenile wild salmon migrate to the ocean) per salmon in net-pens.

Different treatments have been used to remove sea lice: chemical, mechanical, and biological methods. The salmon industry has been employing chemical treatments for decades with chemicals administrated through feeding or bathing (Burridge et al., 2010). In 2018, emamectin benzoate was the most used delousing chemical in feeds, and hydrogen peroxide the most applied through baths (BarentsWatch, 2020). Baths are performed directly in net-pens, by crowding salmon in a tarpaulin or onboard well-boats. Mechanical treatments appeared only a few years ago through the development of processing units flushing and brushing off salmon lice. Thermal delousing was the most common mechanical treatment used in 2017, using lukewarm seawater exposure and turbulences for delousing (Overton et al., 2018). Mechanical units are usually deployed on well-boats, barges or floatable containers, and salmon are crowded in their net-pens and pumped through the processing unit. Cleaner fish feeding on sea lice are used as biological treatment. This treatment method has also been used by farmers for decades, but it is only in recent years that it gained momentum, and organized supply chains emerged. Currently, farmers are using lumpfish (*Cyclopterus lumpus*), and five species of Labridae: ballan wrasse (*Labrus bergylta*), goldsinny wrasse (*Ctenolabrus rupestris*), corkwing wrasse (*Symphodus melops*), rock cook (*Centrolabrus exoletus*) and to a lesser extend cuckoo wrasse (*Labrus mixtus*) (BarentsWatch, 2020).

In recent years, the number of treatments per ton[1] of salmon have increased and shifted from chemical to a mix of biological and mechanical methods due to lice resistance to chemotherapeutants (Aaen et al., 2015). The average use of chemical, mechanical, and biological treatments changed drastically between the periods 2012–2015 and 2016–2019, with chemical use dropping by 42% and mechanical and biological increasing by 1068% and 158%, respectively (BarentsWatch, 2020). For biological treatment, hereafter called biological lice treatments (BLT), the average deployment of cleaner fish in salmon net-pens went from approximately 14.5 to 37.5 million fish between the two time periods (BarentsWatch, 2020). The mix of cleaner fish used also evolved with the emergence of farming of the species in recent years (Helland et al., 2014; Powell et al., 2018). Increasing use of resources and shifts in lice treatment methods are raising economic and environmental concerns (Liu & Bjelland, 2014).

Environmental impacts from disease and parasites associated to food products are mostly unknown, but some research is emerging (Hospido & Sonesson, 2005; Mostert et al., 2018; Williams et al., 2015). Local ecological impacts of disease and parasites in aquaculture are well documented (Johnson et al., 2004; Kristoffersen et al., 2009; Paperna, 1991) but attempts to incorporate such impacts to the life cycle assessment (LCA) framework (with consensus) remain challenging (Bohnes & Laurent, 2018; Cao et al., 2013; Henriksson et al., 2013). Efforts to quantify the life cycle impacts of disease and parasites treatments are deficient, primarily focusing on chemotherapeutants from washing agents, antibiotics, and vaccines (Bohnes et al., 2018). So far, LCAs of salmonids produced in net pen have excluded lice treatments from their inventories (Philis et al., 2019); however, recent work underlines the importance to account for impacts of disease and parasites, including their treatments, particularly when livestock mortality and growth rates are impacted (Winther et al., 2020). Here we investigate in detail the life cycle impacts of biological delousing treatments used in Norwegian salmon farming. We quantify emissions and resource use of three alternative productions of cleaner fish as well as the BLT mix used in the Norwegian salmon aquaculture industry.

2 METHODS

LCA is a standardized method (ISO, 2006a, 2006b) used to quantify resource use and environmental impacts. It involves mapping the inputs and outputs of biophysical flows required and generated throughout the supply chains of products and services. Conducting an LCA is an iterative process constructed around four main phases: (1) goal and scope definition, (2) life cycle inventory, (3) life cycle impact assessment, and (4) interpretation (ILCD Handbook, 2010).

[1] Throughout this study the use of "ton" refers to metric ton.

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

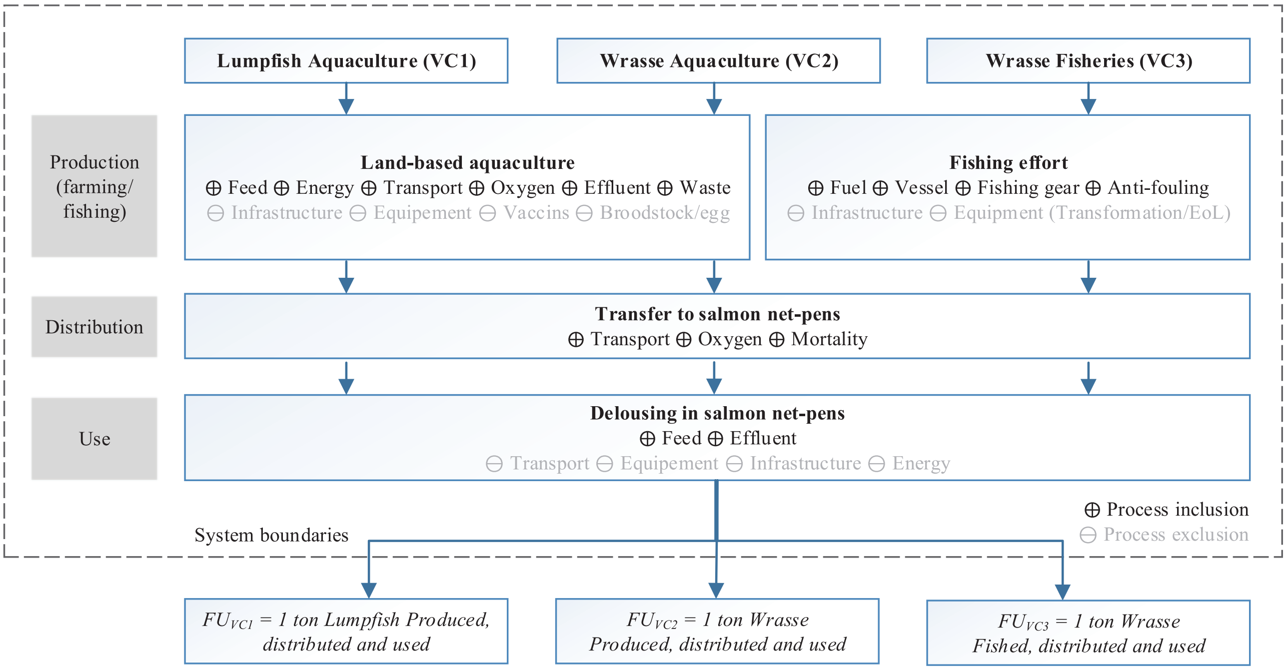

FIGURE 1 Cradle-to-grave system boundaries of VC1-3 forming the BLT used in Norwegian salmon farming

2.1 | Goal and scope definition

The objective of this LCA is dual. Firstly, the study intends to provide a comprehensive picture of impact contribution to identify hotspots in the three cleaner fish value chains (VC1-3) currently supplying Norwegian salmon farmers. Secondly, the study aims to quantify the environmental impacts of the BLT mix used in Norway and hereby evaluate how these impacts contribute to earlier LCA findings on salmon farming.

We conducted this LCA at a national scale, calculating weighted averages (based on production outputs) using representative samples of data sources. A mix of 2017–2019 data was collected from cleaner fish producers, aquafeed manufacturers, fishers, salmon farmers, national statistics, scientific literature, and LCA databases. The three value chains consist of lumpfish aquaculture (VC1), wrasse aquaculture (VC2), and wrasse fisheries (VC3) and are, with different average deployment ratio, forming BLT used by farmers to reduce the prevalence of salmon lice in net-pens. Each value chains consist of three main phases, starting with either farming or fishing, followed by distribution and use (Figure 1). Farmed lumpfish and wrasse are produced in land-based facilities, with an average rearing time of 6 and 18 months, respectively. Species also differ between wrasse value chains (VC2-3) since only ballan wrasse is farmed whereas fishers capture ballan wrasse, goldsinny wrasse, corkwing wrasse, rock cook, and cuckoo wrasse. Farmed lumpfish and fished wrasse dominate cleaner fish supply; farmed wrasse is still in an early development phase.

We selected two different Functional Units (FU) to express the environmental impacts of the value chains and of BLT. For VC1-3, the FU applied was 1 ton of cleaner fish farmed/fished, distributed, and used, following cradle-to-grave system boundaries (Figure 1). Using a functional unit based on mass was preferred to one expressed per fish since each value chains supply cleaner fish with different average weight. We converted the FU of VC1-3 into a number of fish required per ton of salmon using national statistics based on a representative population of Norwegian aquaculture sites to obtain the second FU. Both FUs are imperfect since they are not capturing the delousing efficiency, but the best options available due to lack of knowledge; comparisons between value chains and or with other treatments (mechanical, chemical) need to take this into account. Inclusion and exclusion of processes were based on estimates of expected contribution as well as data quality and availability (Figure 1). The LCA calculations were conducted in Excel and SimaPro v9.

2.2 | Life cycle inventory

Modeling farming and fishing production phases required most data collection. Farmed lumpfish and wrasse are marine species produced in land-based facilities using seawater. Out of the six cleaner fish farmers surveyed, five reported using flow-through technology and one (farming lumpfish) using a more modern recirculating system. Weighted average based on production outputs were applied to VC1-2 based on the number of producers included (VC1) or the number of production years modeled (VC2). Data from Norwegian and Swedish wrasse fishers were collected during the summers of 2018–2019. The results of the survey were divided into geographic zones starting in Sweden, near Gothenburg, moving along the Norwegian coastline, up until Nord-Trøndelag. We combined national statistics to the survey's results to scale up the processes. In 2018, the import of

TABLE 1 List of the primary data collected to model VC1-3 and BLT

Inventory type	Source	Collection	Year & representativity
Farming VC1	5 lumpfish farmers	Questionnaire, visit, calls	2017, 21% (of production)
Farming VC2	1 wrasse farmer	Questionnaire, visit, calls	2017–2018, 12–26% (of production)
Fishing VC3	61 Norwegian fishers 5 Swedish fishers Fishing statistics FDir	Phone survey Questionnaire Application to FDir	2018, 8% (of fishers) 2018, 36% (of fishers) 2018, 100% (of fishers)
Aquafeed	3 feed manufacturers	Questionnaire, calls	2017, NA
Distribution VC1-3	1 distributor	Questionnaire, calls	2018, NA
Use VC1-3	2 feed manufacturers	Questionnaire, calls	2017–2019, 100–85% (of production)
Deployment VC1-3	Treatment statistics BW for 307 localities Biomass statistics FDir for 307 localities	Downloaded from BW a Application to FDir	2017–2019, 36% (of localities) 2017–2019, 36% (of localities)

Note. VC1, lumpfish aquaculture; VC2, wrasse aquaculture; VC3, wrasse fisheries; BW, BarentsWatch; FDir, the Norwegian Directorate of Fisheries; NA, not applicable.

Swedish wrasse represented approximately 4% of the fished wrasse biomass deployed in the Norwegian net-pens. The distribution phases of VC1-3 were modeled based on the data of one distributor as well as information from the cleaner fish producers, fishers, and salmon farmers.

Aquafeed processes are necessary inputs to VC1-3 during both production and/or use phases. Cleaner fish require a variety of extruded and live feed according to their species and development stage (lice eating is a side activity for cleaner fish and not their primary source of nutrients). We modelled eight feed recipes from the feed manufacturers' data and three feed processes from open literature. For the use phase, we opted for a top-down approach, for which we gathered national lumpfish and wrasse feed sales from the main market actors. Nitrogen and phosphorus emissions to water from fish metabolism were calculated using a simple mass-balance approach based on the nutrient concentration in feeds, fish, and the collected slurry.

To calculate BLT impacts, we used records of cleaner fish deployment in salmon net-pens from BarentsWatch (BW) and the salmon biomass statistics from the Norwegian Directorate of Fisheries (FDir). We selected the BW cleaner fish deployment data for our baseline calculations over data provided by FDir since only BW data was available at the locality level. The difference of resolution and number of cleaner fish deployed reported by each institution is linked to their respective data collection methodology. BW receives the number of cleaner fish used from all the localities' production software automatically, while FDir collects the same data by asking aquaculture companies each year how many cleaner fish they have purchased and deployed. We selected localities with a full production cycle comprising 104 weeks of continuous production, between the beginning of 2017 and mid-2019. We excluded localities producing broodstock but included those using green licenses and producing ecological salmon (or trout). For each locality, the ratios of usage of the different cleaner fish were compiled, and a weighted average representative of BLT of the Norwegian production was derived. Impacts from BLT were calculated by multiplying the value chains' life cycle impacts (per fish) with the average cleaner fish mix used by Norwegian farmers.

We completed the model using Ecoinvent v3.5 (allocation, cut-off by classification), Agri-footprint v4.0 (using mass allocation), and AGRIBALYSE v1.3 (based on Ecoinvent cut-off system) LCA databases, as well as a range of assumptions. Foreground allocation based on biomass and time were conducted in VC3, focusing on the boat's construction materials and antifouling paint. A detailed description of sources, inputs, outputs, allocations and assumptions are available in the supporting information uploaded in a Zenodo repository (Philis et al., 2021). Table 1 gives an overview of the primary data collection used to model the three cleaner fish value chains and BLT.

2.3 | Life cycle impact assessment

Impact assessment was performed using ReCiPe 2016 Midpoint (H) v1.03, Cumulative Energy Demand (CED; MJ-eq) v1.11, and the AWARE Water Use (WU; m^3) v1.02 characterization methods. We selected four categories from ReCiPe: Climate Change (CC; kg CO_2 eq), Marine Eutrophication (MEU; kg N eq), Marine Ecotoxicity (MET; kg 1,4-DCB eq), and Land Use (LU; m^2a crop eq). CED is a single issue commonly used in salmonid LCAs to complete sets of midpoint impact categories (Philis et al., 2019). It measures the cumulative energy requirement of the production system, including both renewable and non-renewable sources. AWARE is a consensual water footprint method characterizing available water remaining resulting from the work of Boulay and colleagues (2018) and endorsed by the EU Join Research Center. These impact categories convert the cumulative energy and material requirements as well as emissions to air, water, and soils generated throughout the supply chains' tiers. For instance, this means that hydropower sourced electricity used to produce truck parts can generate WU and LU effects contributing to the overall transportation impacts.

We picked midpoint impacts to ensure the comparability of the results with published salmon LCAs. These six midpoint categories were selected to ensure meaningful process contribution comparisons between value chains.

2.4 | Uncertainty, sensitivity, and scenarios

Uncertainties are present from the data collection to the selection and use of characterization methods. We conducted a Monte Carlo simulation in SimaPro using 1000 iterations and a confidence interval of 95% to account for some of the uncertainty in the data. We accounted for the uncertainty generated by data variability between producers (VC1-2) and between fishing regions (VC3) using a triangular function (with a minimum and maximum) for the inputs and outputs values of the final processes (primarily for the production and fishing phase). In this LCA, baseline modeling used the Norwegian electricity production mix (including imports); this may be controversial because it varies greatly if one considers the physical or market-driven distribution of electricity. The physical approach suggests that the electricity consumed by Norwegian companies mirrors the Norwegian electricity production, i.e., almost exclusively hydropower. The market-driven perspective takes into account energy transactions between Norway and other European countries, resulting in an electricity mix much richer in fossil and nuclear sources (NVE-RME, 2019). We tested the sensitivity of results to this modeling choice by replacing the Norwegian electricity mix with the European mix. Lastly, we conducted two scenarios to investigate the effect of data choice and change in production: 1) cleaner fish deployment data from BW was replaced by numbers collected by FDir, which are reporting significantly higher cleaner fish use in net pens for the 2017–2019 period, and 2) Norwegian authorities will forbid wrasse fishing, leading to all fished wrasse being replaced by farmed wrasse on a one to one basis.

3 | RESULTS

3.1 | Life cycle inventory

The five lumpfish farmers we surveyed produced 6.5 million lumpfish in 2017. Their production volume varied from above two million to a couple hundred thousand fish per year. The modernity, technology, scale, and location of production sites differ significantly. Producers 2–5 are operating reconverted flow-through aquaculture systems, whereas producer 1 has been using a recirculating seawater system with a drum-filter and bioreactor. This farmer reported an economic Feed Conversion Ratio (eFCR) of 0.8, while others range between 1 and 1.2. Producer 3 (the northernmost farmer) used 43,000 kWh per ton of fish due to an old pumping system and more energy expenditure to warm seawater, particularly in the winter. In comparison, other farmers need between 4000 to 20,000 kWh per ton of fish. Nitrogen emissions of producers 2–5 are between 65 and 81 kg per ton of lumpfish, with variations driven by eFCR and feed composition differences; producer 1 emits around ten times less nutrients due to the recirculating technology coupled with the lowest eFCR (see Philis et al., 2021, file "SI Lumpfish Aquaculture").

Production of wrasse in VC2 is taking place in a reconverted flow-through facility that generated 145,000 and 495,000 fish in 2017–2018. The inventory varied drastically within this period, with the eFCR decreasing from 3 to 1.1 due to a significant reduction of mortality (from disease) and major yield improvements in the second year. Following this, electricity use decreased from 209,000 to 61,500 kWh, cumulative transportation from 93,300 to 48,500 tkm, and nitrogen emissions from 180 to 54 kg per ton wrasse (see Philis et al., 2021, file "SI Wrasse Aquaculture").

Inventory variances also occurred between wrasse fishing zones. The fuel consumption of the fishing fleet fluctuates between 800 and 1500 liters per ton of wrasse captured, with southern Norway performing best and Sweden and Møre and Romsdal worst. Vessels and gears used by fishers also differ based on location. The Swedish fleet has the highest fish to boat/trap ratio, resulting in the lowest material requirements, while fishers operating north of Trondheim use most equipment per FU. The use of antifouling paint is relatively even in Norway with values ranging between 0.8 and 1.1 kg while the Swedish fishery is using 3 to 4 times less due to its high capture rate per vessel (see Philis et al., 2021, file "SI Wrasse Fisheries").

The distribution patterns of cleaner fish differ between and within VC1-3. In VC3, most wrasse fished south of Stavanger (southern Norway) are distributed to the salmon farmers by trucks equipped with seawater tanks. Fishers operating north of Stavanger distribute wrasse using their boat or hire the services of well-boat companies. Farmed lumpfish are distributed by trucks and well-boats, while farmed wrasse are transported by lorry only. Overall, farmed and wrasse fished in the south require the most transport. Mortality during transport was estimated at 1% for VC1-2 and 6% for VC3, based on feedbacks from the distributor and fishers. VC3 mortality is higher due to the storage period between fishing and distribution.

All feeds used have a high concentration in marine ingredients derived from fish, krill, shrimp, and squid; inclusions range from 44 to 97%, with cleaner fish feed 2 containing the least and aglonorse/nofima and otohime the most. Two feeds stand out from the others: cleaner fish feed 2 contained the highest concentration of plant-based ingredients (including Brazilian soy), and otohime included 42% krill meal (see Philis et al., 2021, file "SI Feed"). Table 2 provides an aggregated weighted average list of the inventory data collected from the producers and fishers and used to model VC1-3.

Cleaner fish deployment statistics for BLT showed that farmers used an average of 18.6 farmed lumpfish, 0.6 farmed wrasse, and 13 fished wrasse per ton of live-weight salmon produced. This average is based on all 307 localities, with some aquaculture sites using cleaner fish and some not. The

TABLE 2 VC1-3 input and output required and generated per ton of cleaner fish used (i.e., farmed/fished, distributed, and used). More detailed inventories are available in the data repository files "SI Lumpfish Aquaculture", "SI Wrasse Aquaculture", "SI Wrasse Fisheries" https://doi.org/10.5281/zenodo.4121848

Inventory	VC1	VC2	VC3
Cleaner fish (units)	24,715	29,412	23,035
Feed, pellets (kg)	1,966	1,645	248
Feed, live (kg)	5.5	217	–
Electricity (kWh)	17,128	95,076	–
Diesel (l)	14	171	525
Gasoline (l)	0.2	–	672
Transport (tkm)	15,151	58,666	10,266
Oxygen (kg)	473	957	27
Formic acid (kg)	66	38	26
Clay (kg)	–	496	–
Carbon dioxide (kg)	–	69	-
Solid waste (kg)	234	286	–
Fish silage (kg)	1,088	659	453
Nitrogen (kg)	110	102	16
Phosphorus (kg)	17	15	2.2
Vessel materials (kg)	–	–	9.5
Traps materials (kg)	–	–	58
Antifouling paint (kg)	–	–	0.5

Note. VC1, lumpfish aquaculture; VC2, wrasse aquaculture; VC3, wrasse fisheries.

minimum and maximum numbers of fish deployed are ranging between 0–185 farmed lumpfish, 0–20 farmed wrasse, and 0–168 fished wrasse per ton live-weight salmon produced (see Philis et al., 2021, file "SI Cleaner Fish Deployment").

3.2 | Life cycle impact assessment

3.2.1 | Absolute values

Environmental impacts per FU differ significantly between value chains (Figure 2). Farmed wrasse dominates impacts for CC, MET, WU, and CED while farmed lumpfish score highest on MEU and LU. Impacts of farmed wrasse are particularly high for MET, WU, and CED, with scores at least twofold larger than other value chains. Fisheries outperform farming in all categories, with particularly low impacts on MEU, MET, WU, and CED, for which it displays relative values ranging from 2 to 17% compared to the value chain with the highest score. The Monte Carlo simulation revealed varying uncertainty levels between impact categories and value chains. MET scores of VC1-2 are the most uncertain, with a coefficient of variation of approximately 41%. Uncertainty of other impacts ranges between 12–25%, except for fished wrasse MEU, with an uncertainty score close to zero. We excluded WU uncertainty due to the way water flow modeling impaired the results. The uncertainty of WU ranged between 64–126% for VC1-2, primarily because electricity-based hydropower and agricultural processes involved capture and release of water, which artificially increase the uncertainty range calculated with the Monte Carlo simulation. Multiplying the number of cleaner fish deployed by their respective value chain impacts allows to derive BLT results. These results indicate that an average ton of farmgate Norwegian salmonid generate 8.02 kg CO2 eq, 0.1 kg N eq, 0.19 kg 1,4 DCB, 1.21 m2a crop eq, 0.65 m3 and 0.18 GJ of environmental impacts due to BLT.

3.2.2 | Contribution analysis

Figure 3 displays the process contribution of the three chains. Impact distribution appears fairly homogenous for VC1-2. Feed is the largest contributor to three of the six impact categories: CC (72;44%), LU (95;68%), and WU (89;89%) for VC1 and VC2, respectively. Electricity required for farming dominates the impacts of MET (55;72%) and CED (48;69%), especially in VC2.

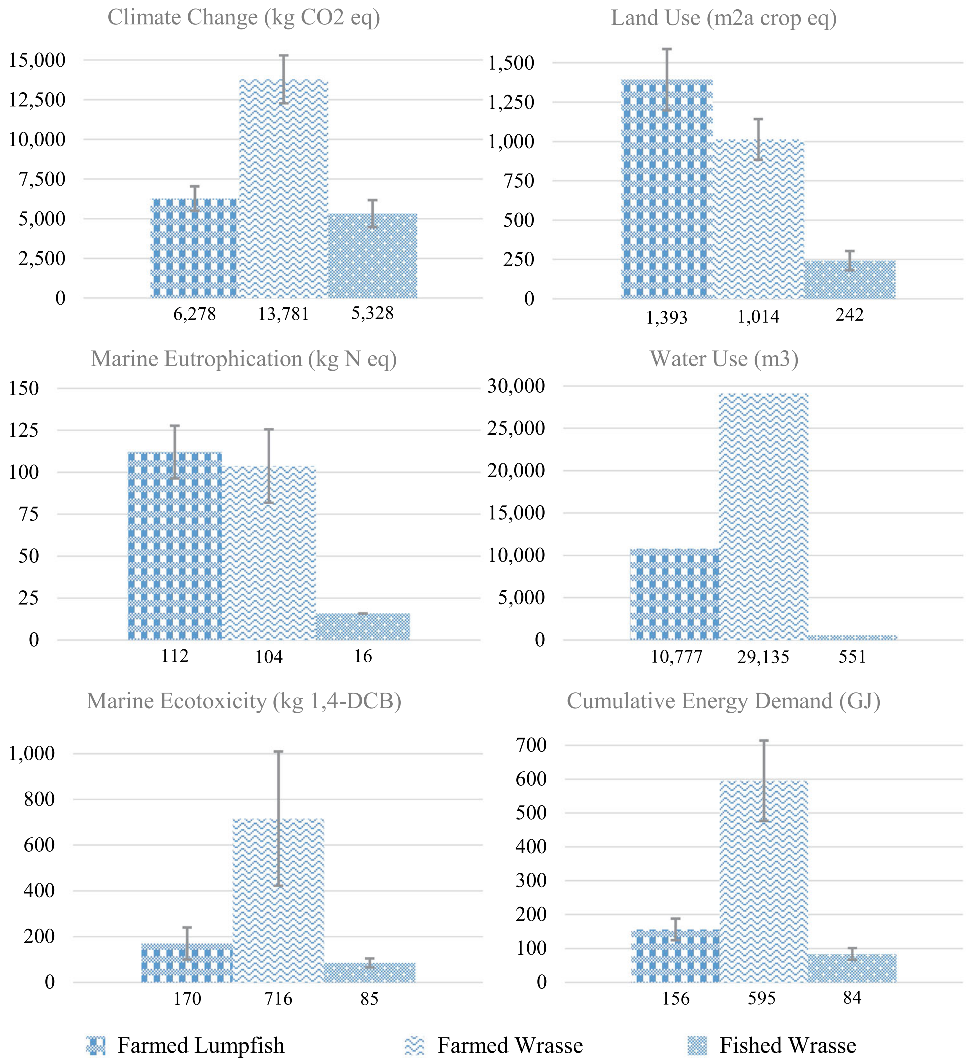

FIGURE 2 Life cycle impacts of VC1-3 per ton of cleaner fish produced/fished, distributed, and used (exact values are displayed under each graphs). Results include foreground and background inventory uncertainty estimated using Monte Carlo simulation (error bars). The elementary data used to create this graph is available on Zenodo in the repository file "SI LCIA Results" (https://doi.org/10.5281/zenodo.4121848)

Other processes like oxygen, waste management, and "remainder" (formic acid, fossil fuels) contribute between 0 to 9% to the different impact categories of VC1 and 0 to 6% of VC2. Transport remains a low contributor to VC1, with impacts ranging from 0 to 10% but account for noticeable effects on CC, LU, and CED of VC2. Wrasse fisheries' contributions differ from the two other value chains. Fuel use (both diesel and gasoline) accounts for 68% of both CC and CED and transportation contribute significantly to MET (27%), LU (28%), CED (19%), CC (17%) and WU (8%). Feed impacts are low across categories, except for LU, for which they account for 67%. The effects of vessel and gear are marginal, with only a noticeable influence on WU (30%) and MET (16%). Lastly, antifouling paint covering hulls has moderate impacts, with a noteworthy contribution to MET (36%) and WU (24%). For all three value chains, MEU impacts can almost exclusively be attributed to fish effluents. For VC1-2, emissions occur during both production and use, while for VC3, marine eutrophication only happens in the use phase (100%).

Overall, impacts of production phases are relatively homogenous across value chains, with the production phase (farming or fishing) dominating in all categories, except for MEU and LU (Figure 4). The use of cleaner fish in salmon net-pens contributes moderately to environmental impacts, except for MEU and LU of VC1 and VC3, for which it is the primary contributor. A low to moderate contribution gradient between value chains can be observed for the distribution phase, starting with VC1 exhibiting least and VC3 most impacts across categories.

3.3 | Sensitivity and scenarios

The outcome of the aquaculture value chains shows considerable sensitivity to the choice of electricity mix, particularly VC2, with the highest electricity consumption (Table 3). Replacing the Norwegian electricity mix with the European mix (which has approximately 15 times higher global

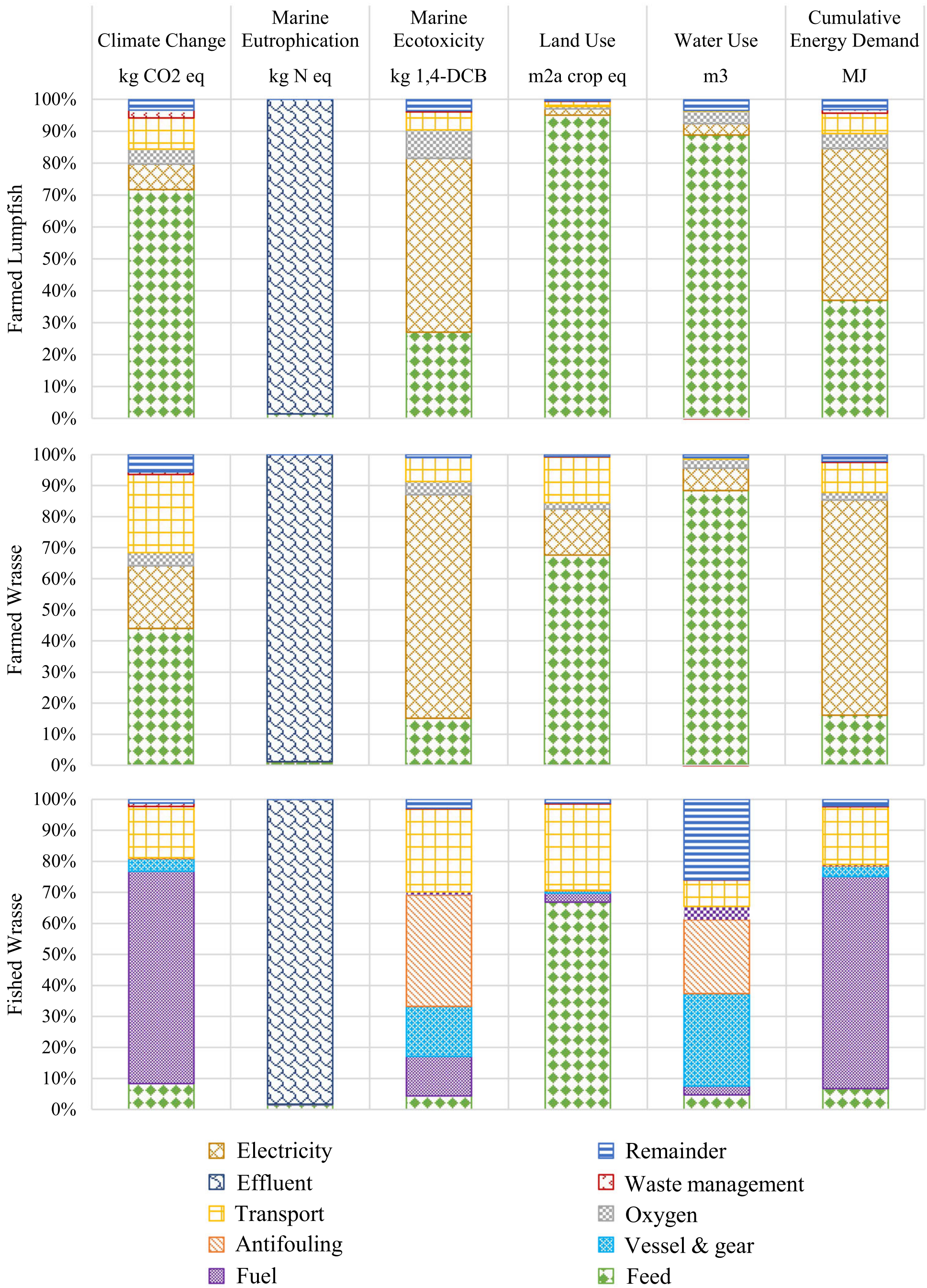

FIGURE 3 Life cycle contribution of processes used across VC1-3. Impacts are calculated per ton of cleaner fish farmed/fished, distributed, and used, and are presented in relative values. The elementary data used to create this graph is available on Zenodo in the repository file "SI LCIA Results" (https://doi.org/10.5281/zenodo.4121848)

warming potential per kWh used), modifies all VC1-2 impacts but MEU substantially. Scores drastically increase for CC, MET, LU (in VC2), CED and to a lesser extent, for LU (in VC1) and WU. On the opposite, VC3 is unaffected by the change of mix since its foreground system is electricity-free. The sensitivity of BLT to electricity mixes resembles those of VC1-2 but is dampened by the neutrality of VC3.

The higher use of cleaner fish reported by FDir (compared to BW) linearly increases deployment ratios and consequently BLT impacts. On average, FDir reports between 5 to 45% more cleaner fish deployed during the 2017–2019 period, depending on years and species. The deployment ratio of VC1-3 increase from 25–31% compared to baseline, resulting in a homogeneous rise of 26–27% of all impact categories.

Finally, a ban on wrasse fishing will affect BLT impacts, assuming VC2 would provide a simple one to one replacement. The model is very sensitive to this scenario. BLT impacts increase across all categories, especially MET (+141%), WU (+139%) and CED (+122%); it has the least effect on CC (38%).

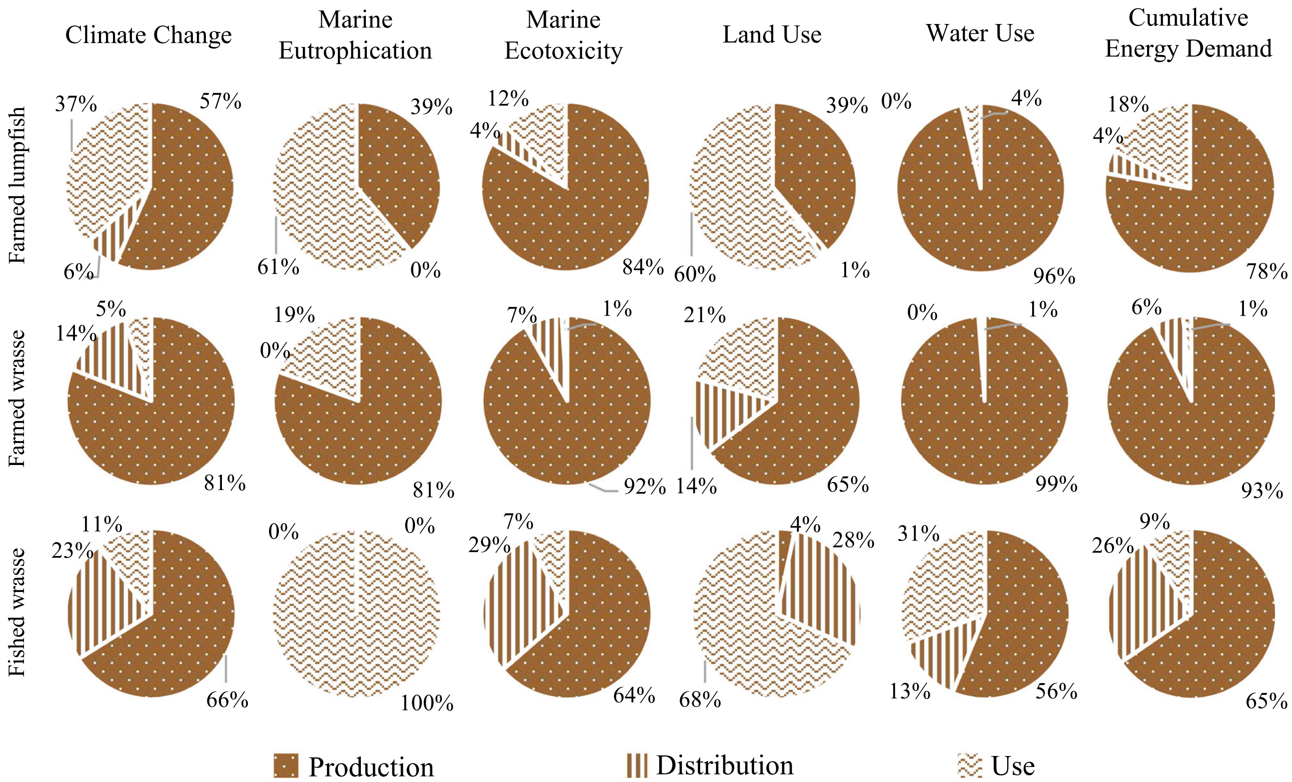

FIGURE 4 Contribution of production phases modeled across VC1-3. Impacts are calculated per ton of cleaner fish produced/fished, distributed, and used and are presented in relative values. The elementary data used to create this graph is available on Zenodo in the repository file "SI LCIA Results" (https://doi.org/10.5281/zenodo.4121848)

TABLE 3 Relative change to the baseline of VC1-3 and BLT impacts, testing sensitivity to alternative electricity mix, deployment data, and a ban of wrasse fishing. The underlying data compiled in this table is available in the repository file "SI LCIA Results" https://doi.org/10.5281/zenodo.4121848

Impact categories	VC1 EU-mix	VC2 EU-mix	VC3 EU-mix	BLT EU-mix	BLT FDir	BLT VC1-2
Climate Change	+112%	+284%	0%	+76%	+26%	+38%
Marine Eutrophication	0%	+3%	0%	0%	+27%	+39%
Marine Ecotoxicity	+171%	+226%	0%	+133%	+27%	+141%
Land Use	+17%	+129%	0%	+17%	+27%	+26%
Water Use	+11%	+24%	0%	+12	+27%	+139%
Cumulative Energy Demand	+72%	+106%	0%	+55%	+27%	+122%

Note. VC1, lumpfish aquaculture; VC2, wrasse aquaculture; VC3, wrasse fisheries; BLT, biological lice treatments; EU-mix, European electricity mix; FDir, the Norwegian Directorate of Fisheries.

4 | DISCUSSION

4.1 | Comparing the life cycle impacts of cleaner fish value chains

Strong biological differences between lumpfish and wrasse and major disparities between farming and fishing activities explain the impact variability of the three cleaner fish value chains.

Two factors are driving the large impacts generated by VC2: (1) it is the newest and smallest value chain, and (2) farming wrasse is more complex and resource-intensive compared to lumpfish. Impact reductions can be expected as VC2 grows and matures (Cucurachi et al., 2018). In fact, the data already show dramatic efficiency improvements between 2017 and 2018 (see Philis et al., 2021, file "SI Wrasse Aquaculture"). Yet, despite optimization and economies of scale, VC2 will probably maintain higher impacts than VC1 and VC3 because of its specific requirements. Wrasse farming has a production cycle three times longer than lumpfish and an unusually high electricity demand despite the use of heat-exchangers (Table 2).

This is partly due to the longer production cycle, higher sea-water temperature requirements (compared to lumpfish), and the current use of flow-through rearing technology (Brooker et al., 2018). Farmed wrasse also requires live feeding through the hatching phase and is particularly prone to disease and adaptation difficulties (Helland et al., 2014). Farmed lumpfish score only higher than farmed wrasse in two of the six impact categories: MEU and LU. The main reasons are higher feed requirements of lumpfish in the salmon net-pens, and to a lesser extent, because lumpfish producer 1 and 5 use a feed richer in agricultural ingredients (cleaner fish feed 2). VC2 shows a higher eFCR than VC1 during production (1.55 vs. 0.96), but considerably lower eFCR during the use phase (0.32 vs. 1.02), suggesting that wrasse are fed less or eat less once deployed in the salmon net-pens. Improvement options for VC1-2 would primarily consist of modernizing the production equipment by converting flow-through into recirculating systems and improving farming practices to reduce mortality and improve efficiency. Krill products are major drivers of CC and MET but replacing them with agricultural ingredients will spike MEU and LU. Overall, VC3 generates by far the lowest life cycle emissions across all categories. Impacts could even be reduced further by lowering engine power and boat sizes, as well as the distances covered during both fishing and distribution.

The sensitivity of VC1-2 to the electricity mix suggests even greater impact differences between farmed and fished cleaner fish if farmers are not supplied with abundant hydropower. Impacts will also rise dramatically across all categories if the Norwegian authorities were to ban wrasse fishing and farmed wrasse compensated the lack of cleaner fish on the market. Although lumpfish and wrasse have distinct prices and blending ratios in net-pens suggesting quantifiable disparities in delousing efficiency, the use ratios reported in localities show relative similarities. Out of 45 (VC1) and 47 (VC2-3) localities using only lumpfish or wrasse, 30 lumpfish and 25 wrasse per ton salmon produced were deployed on average; this would equate to an efficiency difference of 17% in favor of wrasse chains. Such comparison is however dubious. Localities using only lumpfish are also concentrated in northern Norway, where the salmon lice exposure is less compared to the south. Furthermore, differentiation between efficiencies of farmed and fished wrasse cannot be made with the current data.

4.2 | Comparability of delousing efficiencies

Despite our attempt to compare the environmental impacts of the different cleaner fish value chains, a significant gap of knowledge remains to couple life cycle emissions generated by the farming/fishing, distribution, and use of the cleaner fish and their potential different delousing efficiencies in the salmon net-pens. Each of the fish produced by VC1-3 has a similar function (keeping the number of female lice per salmon under 0.5), but their characteristics and efficiencies may vary widely. Differences of attributes affecting lice eating efficiencies are broad: ranging from species types, behavior, survival and adaptation rates, response to stress, growth speed, to operating sea-water temperature, and swimming abilities (Brooker et al., 2018). For instance, farmers north of Trøndelag only use lumpfish since the lower sea temperatures impair wrasse activity, but farmers further south often combine both types. Variability in biological conditions at farming sites complicates the evaluation of delousing efficiencies. Salmon lice pressure between localities depends on a multitude of factors like location, current, stock density, the prevalence of viruses, or the use of other lice treatments (Sandvik et al., 2020). There is also a lack of knowledge about the infestation levels of localities. Current measurements are done manually every week, sampling only 20 fish per cage, which represents around 0.02% of the salmon biomass.

There is a surprisingly high level of uncertainty regarding the cleaner fish delousing efficiency, with a lack of replicated studies performed at full commercial scale for each of the used species (Overton et al., 2020). Some experimental studies found lumpfish (Eliasen et al., 2018; Imsland et al., 2018) and wrasse (Leclercq et al., 2014; Skiftesvik et al., 2013) to be effective delousers. Yet, a recent top-down statistical analysis demonstrates low overall efficiency of BLT, with localities deploying cleaner fish early in their production cycle only gaining a slight delay for other treatments and thus a small reduction of the salmon lice population growth (Barrett et al., 2020).

4.3 | Cleaner fish welfare and LCA limitations

While LCA is an efficient method to account for regional and global environmental impacts generated by anthropogenic activities in value chains, it still lacks a coherent framework to account for local ecological effects and animal welfare (Ford et al., 2012; Scherer et al., 2018; Woods et al., 2016). Despite fishing quotas and seasonal restrictions established by FDir, the long-term effect of removing a large amount of wrasse from their natural environment is not fully understood (Blanco Gonzalez & de Boer, 2017; Halvorsen et al., 2017). Fishers have been reporting declining concentration of wrasse captured per traps, suggesting high fishing pressure (Skiftesvik et al., 2014). Besides, wrasse transport between fishing grounds and salmon net-pens in different counties, or even countries, is highly controversial, introducing foreign fish in ecosystems and potentially spreading disease and parasites (Faust et al., 2018; Murray, 2016).

Cleaner fish welfare is also a central issue debated among stakeholders not covered by this LCA. A recent report of the Norwegian Food Safety Authority made national headlines by reporting 40% of cleaner fish mortality during salmon production cycles (Mattilsynet, 2020). Cleaner fish mortality is particularly high in the weeks following deployment, suggesting that lumpfish and wrasse have difficulties in adapting the net-pen environments. In fact, recent cleaner fish welfare research suggests that salmon can have predatory behavior and bite cleaner fish in net-pens (Espmark et al., 2019). Wrasse seems especially sensitive to environmental stress. Inventory data of VC2-3 show abnormally low eFCR during the use phase (see Philis et al., 2021, files "SI Wrasse Aquaculture" and "SI Wrasse Fisheries). We hypothesize that lower feed inputs are unlikely to originate primarily from farmers' restriction or neglect but more from a general loss of appetite due to stress and/or, in the case of fished wrasse, the inability to feed on extruded pellets.

In reality, there is a cleaner fish mortality ratio of 100% since they are not reused at the end of each salmon production cycle. This is partly because large cleaner fish are suspected to lose their delousing efficiency, as well as disease cross-contamination risks. When salmon is ready to be slaughtered, the remaining cleaner fish are collected and euthanized, mixed with formic acid and sent to biogas facilities. Recent projects are looking for opportunities to valorize cleaner fish biomass for human consumption, pet foods, or nutrient extraction, but are still in an early development phase (FHF, 2020).

4.4 | Treatments contribution to life cycle impacts of salmon

We calculated the contribution of BLT to salmon farming by adding the treatment results to the average life cycle impacts measured per ton live-weight salmon produced in net-pens for CC and CED (Philis et al., 2019). When baseline impacts were added to the 2933 kg CO_2 eq and 38 GJ of the current salmon production estimates, BLT contributed to 0.27 and 0.47% of the new totals. With the European electricity production mix, contribution rose to 0.48 and 0.72%, and if deployment data of FDir was used, BLT accounted for 0.34 and 0.59% of the impacts. Finally, if farmed wrasse replaces fished ones, BLT will represent 0.38 and 1.03% of CC and CED, respectively.

The exclusion of infrastructure underestimates impacts from VC1-2 slightly, but since the production plants were conversions of existing buildings, their effects were estimated to be low (Bergman et al., 2020). Impacts from feed use in net-pens are also likely to be underestimated since it is known that lumpfish eat salmon pellets in addition to their feed (Eliasen et al., 2018), and inventory data indicates that wrasse are undernourished. Despite these small differences, BLT baseline and most BLT scenarios' contributions to salmon impacts remain well under any significant levels. This means that, at present the cleaner fish mix used by the Norwegian aquaculture industry has negligible effects on salmon life cycle impacts. We excluded the contributions of BLT to other impact categories due to the lack of standardized characterization methods between studies. However, results indicate that the BLT contribution is in the same order of magnitude across all six impact categories when compared to salmon. The relatively low contribution to overall emissions of BLT confirms previously reported findings based on rough estimations (Winther et al., 2020) and indicates that an increase in salmon FCR from lice infestation (due to increased mortality, reduced growth and/or salmon feed being eaten by cleaner fish) may have larger influence on salmon life cycle impacts than the impacts of BLT itself. Earlier and more recent LCA studies of farmed salmonid (e.g. Sherry & Koester, 2020; Parker, 2017; Pelletier et al., 2009; Newton & Little, 2017; Ziegler et al., 2013) did not account for sea lice treatments or other parasites and diseases affecting salmon production. Although specific to the Norwegian context, the data and methods presented here could form a basis for including this type of activities in future aquaculture LCAs.

Even if comparisons may be complicated due to lack of data on delousing efficiencies, it remains crucial to assess the current impacts of BLT with the two other lice treatments in order to give guidance for future lice management from an environmental perspective. Recent research suggests that both mechanical and chemical treatments generate significant mortality among salmon; this is likely to have larger contribution to the overall salmon life cycle impacts (Overton et al., 2018). It is also important for future research to assess the total life cycle impacts of disease, including impacts of reduced growth/increased mortality on feed use and increased need for vessel activities on the salmon farm related to treatments (Winther et al., 2020).

5 | CONCLUSIONS

Wrasse fisheries outperform aquaculture-sourced cleaner fish across the six life cycle impact categories considered. Results are strengthened if the electricity used by fish farmers is less based on hydropower. A ban or reduction of wrasse fishing due to local ecological concerns is likely to increase the life cycle environmental impacts of BLT, but not necessarily above any significance level, especially if improvements made by wrasse farmers are sustained. In order to reduce the impacts of cleaner fish farming, we recommend farmers to upgrade their production facility to a recirculating aquaculture system and use feed with less krill. Major impact reductions can also be achieved in wrasse fisheries. We suggest keeping wrasse fishing regional, using small fishing boats with low engine power, and reducing distances between capture and delivery of wrasse to salmon farmers. Relocating operations could also reduce storage time and mortality rates.

Overall, BLT impacts are low compared to the impacts of farmgate salmon and, based on the different scenarios investigated, unlikely to contribute significantly to the salmon life cycle impacts. However, the lack of evidence of cleaner fish delousing efficiency in the literature is problematic since low BLT impacts could be counter-weighted by low efficiency. This will be measurable when a FU capturing BLT delousing capabilities will be developed. Assessing the environmental impacts of biological, mechanical, and chemical treatments is essential, nonetheless. It generates the fundamental data required to add contribution of treatments to the salmon footprints and is necessary to assess which treatment mix used by salmon farmers could generate the lowest impacts. Further research is needed to quantify potentially different cleaner fish efficiency and ways to alleviate poor cleaner fish welfare currently reported in net-pens. Additional studies are necessary to quantify the life cycle impacts of mechanical and chemical lice treatments and develop more comprehensive LCA practices accounting for the direct and indirect environmental impacts of disease, parasites, and their treatments in animal-based food LCAs.

ACKNOWLEDGMENTS

The authors would like to thank all the companies and dedicated employees that agreed to share data with them. They cannot be named due to confidentiality but deserve our sincere gratitude, nonetheless. Building the inventories of this model could not have been possible without them. The authors also wish to acknowledge the participation of Ludivine Lafosse, Annalin Fasting, Catrine Schulze, Reidun Stiand during their bachelor thesis work. Finally, the authors would like to express their appreciation to Mats Snåre for providing a well-needed perspective from the salmon farming side.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

FUNDING INFORMATION

This research was funded through the NTNU Sustainability Strategic Research Area and the Swedish Research Council FORMAS (grant number 2016-00455).

ORCID

Gaspard Philis https://orcid.org/0000-0002-5630-8157
Friederike Ziegler https://orcid.org/0000-0003-1995-2338
Mona Dverdal Jansen https://orcid.org/0000-0002-7151-3415
Lars Christian Gansel https://orcid.org/0000-0003-3316-5277
Sara Hornborg https://orcid.org/0000-0003-0814-5258
Grete Hansen Aas https://orcid.org/0000-0003-4643-4755

REFERENCES

Aaen, S. M., Helgesen, K. O., Bakke, M. J., Kaur, K., & Horsberg, T. E. (2015). Drug resistance in sea lice: a threat to salmonid aquaculture. *Trends in Parasitology*, *31*(2), 72–81. https://doi.org/10.1016/j.pt.2014.12.006

Abolofia, J., Asche, F., & Wilen, J. (2017). The cost of lice: quantifying the impacts of parasitic sea lice on farmed salmon. *Marine Resource Economics*, *32*(3), 329–349. https://doi.org/10.1086/691981

BarentsWatch. (2020). *Treatment against sealice*. https://www.barentswatch.no/en/download/fishhealth/treatments

Barrett, L. T., Overton, K., Stien, L. H., Oppedal, F., & Dempster, T. (2020). Effect of cleaner fish on sea lice in Norwegian salmon aquaculture: a national scale data analysis. *International Journal for Parasitology*, *50*(10-11), 787–796. https://doi.org/10.1016/j.ijpara.2019.12.005

Bergman, K., Henriksson, P. J. G., Hornborg, S., Troell, M., Borthwick, L., Jonell, M., Philis, G., & Ziegler, F. (2020). Recirculating aquaculture is possible without major energy tradeoff: Life cycle assessment of warmwater fish farming in Sweden. *Environmental Science & Technology*, *54*(24). https://doi.org/10.1021/acs.est.0c01100

Blanco Gonzalez, E., & de Boer, F. (2017). The development of the Norwegian wrasse fishery and the use of wrasses as cleaner fish in the salmon aquaculture industry. *Fisheries Science*, *83*(5), 661–670. https://doi.org/10.1007/s12562-017-1110-4

Bohnes, F. A., Hauschild, M. Z., Schlundt, J., & Laurent, A. (2018). Life cycle assessments of aquaculture systems: a critical review of reported findings with recommendations for policy and system development. *Reviews in Aquaculture*, *11*(4)https://doi.org/10.1111/raq.12280

Bohnes, F. A., & Laurent, A. (2018). LCA of aquaculture systems: methodological issues and potential improvements. *The International Journal of Life Cycle Assessment*, https://doi.org/10.1007/s11367-018-1517-x

Boulay, A.-M., Bare, J., Benini, L., Berger, M., Lathuillière, M. J., Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A. V., Ridoutt, B., Oki, T., Worbe, S., & Pfister, S. (2018). The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). *The International Journal of Life Cycle Assessment*, *23*(2), 368–378. https://doi.org/10.1007/s11367-017-1333-8

Brooker, A. J., Papadopoulou, A., Gutierrez, C., Rey, S., Davie, A., & Migaud, H. (2018). Sustainable production and use of cleaner fish for the biological control of sea lice: Recent advances and current challenges. *Veterinary Record*, *183*(12), 383. https://doi.org/10.1136/vr.104966

Burridge, L., Weis, J. S., Cabello, F., Pizarro, J., & Bostick, K. (2010). Chemical use in salmon aquaculture: a review of current practices and possible environmental effects. *Aquaculture*, *306*(1-4), 7–23. https://doi.org/10.1016/j.aquaculture.2010.05.020

Cao, L., Diana, J. S., & Keoleian, G. A. (2013). Role of life cycle assessment in sustainable aquaculture. *Reviews in Aquaculture*, *5*(2), 61–71. https://doi.org/10.1111/j.1753-5131.2012.01080.x

Conijn, J. G., Bindraban, P. S., Schröder, J. J., & Jongschaap, R. E. E. (2018). Can our global food system meet food demand within planetary boundaries? *Agriculture, Ecosystems & Environment*, *251*, 244–256. https://doi.org/10.1016/j.agee.2017.06.001

Costello C., Cao L., Gelcich S., Cisneros-Mata M. Á., Free C. M., Froehlich H. E., Golden C. D., Ishimura G., Maier J., Macadam-Somer I., Mangin T., Melnychuk M. C., Miyahara M., de Moor C. L., Naylor R., Nøstbakken L., Ojea E., O'Reilly E., … & Lubchenco J. (2020). The future of food from the sea. *Nature*, *588*, (7836), 95–100. https://doi.org/10.1038/s41586-020-2616-y.

Cucurachi, S., van der Giesen, C., & Guinée, J. (2018). Ex-ante LCA of Emerging Technologies. *Procedia CIRP*, *69*, 463–468. https://doi.org/10.1016/j.procir.2017.11.005

Eliasen, K., Danielsen, E., Johannesen, Á., Joensen, L. L., & Patursson, E. J. J. A. (2018). The cleaning efficacy of lumpfish (*Cyclopterus lumpus* L.) in Faroese salmon (*Salmo salar* L.) farming pens in relation to lumpfish size and seasonality. *Aquaculture*, *488*, 61–65. https://doi.org/10.1016/j.aquaculture.2018.01.026

Espmark, Å. M. O., Noble, C., Kolarevic, J., Berge, G. M., Aas, G. H., Tuene, S. A., Iversen, M. H., Wergeland, H. I., Johansen, L.-H., & Burgerhout, E. (2019). Velferd hos rensefisk-operative velferdsindikatorer (OVI)-RENSVEL. *Nofima rapportserie*, https://nofima.no/publikasjon/1698693/

Faust, E., Halvorsen, K. T., Andersen, P., Knutsen, H., & André, C. (2018). Cleaner fish escape salmon farms and hybridize with local wrasse populations. *Royal Society Open Science*, *5*(3), 171752. https://doi.org/10.1098/rsos.171752

FHF. (2020). *Program rensefisk: Gjenfangst, bedøvelse, avliving og etterbruk av rensefisk (CLEANCATCH)*. https://www.fhf.no/prosjekter/prosjektbasen/901560/

Ford, J. S., Pelletier, N. L., Ziegler, F., Scholz, A. J., Tyedmers, P. H., Sonesson, U., Kruse, S. A., & Silverman, H. (2012). Proposed local ecological impact categories and indicators for life cycle assessment of aquaculture: A salmon aquaculture case study. *Journal of Industrial Ecology*, *16*(2), 254–265. https://doi.org/10.1111/j.1530-9290.2011.00410.x

Halvorsen, K. T., Larsen, T., Sørdalen, T. K., Vøllestad, L. A., Knutsen, H., & Olsen, E. M. (2017). Impact of harvesting cleaner fish for salmonid aquaculture assessed from replicated coastal marine protected areas. *Marine Biology Research*, *13*(4), 359–369. https://doi.org/10.1080/17451000.2016.1262042

Helland, S., Dahle, S., Hough, C., & Borthen, J. (2014). *Production of ballan wrasse (Labrus bergylta)*. https://www.sintef.no/contentassets/431f06e53bc448998fb856156c6799d5/final-report_-production-of-ballan-wrasse_-science-and-practice.pdf

Henriksson, P. J. G., Pelletier, N. L., Troell, M., & Tyedmers, P. H. (2013). Life cycle assessments and their applications to aquaculture production systems life cycle assessment (LCA) aquaculture production systems. In: Christou, P., Savin, R., Costa-Pierce, B. A., Misztal, I. & Whitelaw, C. B. A. (eds.). In *Sustainable food production* (pp. 1050–1066). Springer. https://doi.org/10.1007/978-1-4614-5797-8_191

Hjeltnes, B., Bang-Jansen, B., Bornø, G., Haukaas, A., & Walde, C. S. (2019). *The health situation in Norwegian aquaculture 2018*. Norwegian Veterinary Institute. https://www.vetinst.no/rapporter-og-publikasjoner/rapporter/2019/fish-health-report-2018

Hospido, A., & Sonesson, U. (2005). The environmental impact of mastitis: a case study of dairy herds. *Science of the Total Environment*, *343*(1), 71–82. https://doi.org/10.1016/j.scitotenv.2004.10.006

ILCD Handbook. (2010). *General guide for life cycle assessment, detailed guidance*. European Commission, Joint Research Centre. https://eplca.jrc.ec.europa.eu/ilcd.html

Imsland, A. K. D., Hanssen, A., Nytrø, A. V., Reynolds, P., Jonassen, T. M., Hangstad, T. A., Elvegård, T. A., Urskog, T. C., & Mikalsen, B. (2018). It works! Lumpfish can significantly lower sea lice infestation in large-scale salmon farming. *Biology Open*, *7*(9), bio036301. https://doi.org/10.1242/bio.036301

ISO. (2006a). ISO 14040:2006. Environmental management – Life cycle assessment – Principles and framework. https://www.iso.org/standard/37456.html

ISO. (2006b). ISO 14044:2006. Environmental management – Life cycle assessment – Requirements and guidelines. https://www.iso.org/standard/38498.html

Jansen, M., Bang Jensen, B., McLoughlin, M., Rodger, H., Taksdal, T., Sindre, H., Graham, D., & Lillehaug, A. (2017). The epidemiology of pancreas disease in salmonid aquaculture: a summary of the current state of knowledge. *Journal of Fish Diseases*, *40*(1), 141–155. https://doi.org/10.1111/jfd.12478

Johnson, S. C., Bravo, S., Nagasawa, K., Kabata, Z., Hwang, J., Ho, J., & Shih, C. (2004). A review of the impact of parasitic copepods on marine aquaculture. *Zoological studies*, *43*(2), 229–243.

Kristoffersen, A. B., Viljugrein, H., Kongtorp, R. T., Brun, E., & Jansen, P. A. (2009). Risk factors for pancreas disease (PD) outbreaks in farmed Atlantic salmon and rainbow trout in Norway during 2003–2007. *Preventive Veterinary Medicine*, *90*(1), 127–136. https://doi.org/10.1016/j.prevetmed.2009.04.003

Leclercq, E., Davie, A., & Migaud, H. (2014). Delousing efficiency of farmed ballan wrasse (*Labrus bergylta*) against *Lepeophtheirus salmonis* infecting Atlantic salmon (*Salmo salar*) post-smolts. *Pest Management Science*, *70*(8), 1274–1282. https://doi.org/10.1002/ps.3692

Liu, Y., & Bjelland, H. v. (2014). Estimating costs of sea lice control strategy in Norway. *Preventive Veterinary Medicine*, *117*(3), 469–477. https://doi.org/10.1016/j.prevetmed.2014.08.018

Mattilsynet. (2020). *Nasjonal tilsynskampanje 2018/2019 - Velferd hos rensefisk*. https://www.mattilsynet.no/fisk_og_akvakultur/akvakultur/rensefisk/rensefiskkampanje_20182019.30882

Meld.St.16. (2014-2015). *Forutsigbar og miljømessig bærekraftig vekst i norsk lakse- og ørretoppdrett*. Ministry of Trade, Industry and Fisheries. https://www.regjeringen.no/contentassets/6d27616f18af458aa930f4db9492fbe5/no/pdfs/stm201420150016000dddpdfs.pdf

Mostert, P. F., van Middelaar, C. E., Bokkers, E. A. M., & de Boer, I. J. M. (2018). The impact of subclinical ketosis in dairy cows on greenhouse gas emissions of milk production. *Journal of Cleaner Production*, *171*, 773–782. https://doi.org/10.1016/j.jclepro.2017.10.019

Murray, A. G. (2016). A Modelling Framework for Assessing the Risk of Emerging Diseases Associated with the Use of Cleaner Fish to Control Parasitic Sea Lice on Salmon Farms. *Transboundary and Emerging Diseases*, *63*(2), 270–277. https://doi.org/10.1111/tbed.12273

Newton, R. W., & Little, D. C. (2017). Mapping the impacts of farmed Scottish salmon from a life cycle perspective. *The International Journal of Life Cycle Assessment*, https://doi.org/10.1007/s11367-017-1386-8

NVE-RME. (2019). *Electricity disclosure 2018*. https://www.nve.no/norwegian-energy-regulatory-authority/retail-market/electricity-disclosure-2018/

Overton, K., Barrett, L. T., Oppedal, F., Kristiansen, T. S., & Dempster, T. (2020). Sea lice removal by cleaner fish in salmon aquaculture: A review of the evidence base. *Aquaculture Environment Interactions*, *12*, 31–44. https://doi.org/10.3354/aei00345

Overton, K., Dempster, T., Oppedal, F., Kristiansen, T. S., Gismervik, K., & Stien, L. H. (2018). Salmon lice treatments and salmon mortality in Norwegian aquaculture: A review. *Reviews in Aquaculture*, 1–20. https://doi.org/10.1111/raq.12299

Paperna, I. (1991). Diseases caused by parasites in the aquaculture of warm water fish. *Annual Review of Fish Diseases*, *1*, 155–194. https://doi.org/10.1016/0959-8030(91)90028-I

Parker, R. (2017). Implications of high animal by-product feed inputs in life cycle assessments of farmed Atlantic salmon. *The International Journal of Life Cycle Assessment*, https://doi.org/10.1007/s11367-017-1340-9

Pelletier, N., Tyedmers, P., Sonesson, U., Scholz, A., Ziegler, F., Flysjo, A., Kruse, S., Cancino, B., & Silverman, H. (2009). Not all salmon are created equal: life cycle assessment (LCA) of global salmon farming systems. *Environmental Science & Technology*, *43*(23), 8730–8736. https://doi.org/10.1021/es9010114

Philis, G., Ziegler, F., Gansel, L. C., Jansen, M. D., Gracey, E. O., & Stene, A. (2019). Comparing Life Cycle Assessment (LCA) of Salmonid Aquaculture Production Systems: Status and Perspectives. *Sustainability*, *11*(9), 2517. https://doi.org/10.3390/su11092517

Philis, G., Ziegler, F., Jansen, M. D., Gansel, L. C., Hornborg, S., Aas Hansen, G., & Stene, A. (2021). Supporting Information for: Quantifying environmental impacts of cleaner fish used as sea lice treatments in salmon aquaculture with Life Cycle Assessment (LCA). *Zenodo*, https://doi.org/10.5281/zenodo.4121848

Powell, A., Treasurer, J. W., Pooley, C. L., Keay, A. J., Lloyd, R., Imsland, A. K., & Garcia de Leaniz, C. (2018). Use of lumpfish for sea-lice control in salmon farming: challenges and opportunities. *Reviews in Aquaculture*, *10*(3), 683–702. https://doi.org/10.1111/raq.12194

Sandvik, A. D., Johnsen, I. A., Myksvoll, M. S., Sævik, P. N., & Skogen, M. D. (2020). Prediction of the salmon lice infestation pressure in a Norwegian fjord. *ICES Journal of Marine Science*, *77*(2), 746–756. https://doi.org/10.1093/icesjms/fsz256

Scherer, L., Tomasik, B., Rueda, O., & Pfister, S. (2018). Framework for integrating animal welfare into life cycle sustainability assessment. *The International Journal of Life Cycle Assessment*, *23*(7), 1476–1490. https://doi.org/10.1007/s11367-017-1420-x

Sherry, J., & Koester, J. (2020). Life cycle assessment of Aquaculture Stewardship Council certified Atlantic Salmon (*Salmo salar*). *Sustainability*, *12*(15), 6079. https://doi.org/10.3390/su12156079

Skiftesvik, A. B., Bjelland, R. M., Durif, C. M., Johansen, I. S., & Browman, H. (2013). Delousing of Atlantic salmon (*Salmo salar*) by cultured vs. wild ballan wrasse (*Labrus bergylta*). *Aquaculture*, *402*, 113–118. https://doi.org/10.1016/j.aquaculture.2013.03.032

Skiftesvik, A. B., Blom, G., Agnalt, A.-L., Durif, C. M., Browman, H. I., Bjelland, R. M., Harkestad, L. S., Farestveit, E., Paulsen, O. I., & Fauske, M. (2014). Wrasse (Labridae) as cleaner fish in salmonid aquaculture–the Hardangerfjord as a case study. *Marine Biology Research*, *10*(3), 289–300. https://doi.org/10.1080/17451000.2013.810760

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B. L., Lassaletta, L., de Vries, W., Vermeulen, S. J., Herrero, M., Carlson, K. M., Jonell, M., Troell, M., DeClerck, F., Gordon, L. J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., … Willett, W. (2018). Options for keeping the food system within environmental limits. *Nature*, *562*(7728), 519–525. https://doi.org/10.1038/s41586-018-0594-0

Taranger, G. L., Karlsen, Ø., Bannister, R. J., Glover, K. A., Husa, V., Karlsbakk, E., Kvamme, B. O., Boxaspen, K. K., Bjørn, P. A., & Finstad, B. (2014). Risk assessment of the environmental impact of Norwegian Atlantic salmon farming. *ICES Journal of Marine Science*, *72*(3), 997–1021. https://doi.org/10.1093/icesjms/fsu132

Williams, A., Chatterton, J., Hateley, G., Curwen, A., & Elliott, J. (2015). A systems-life cycle assessment approach to modelling the impact of improvements in cattle health on greenhouse gas emissions. *Advances in Animal Biosciences*, *6*(1), 29–31. https://doi.org/10.1017/S2040470014000478

Winther, U., Hognes, E. S., Jafarzadeh, S., & Ziegler, F. (2020). *Greenhouse gas emissions of Norwegian seafood products in 2017*. https://www.sintef.no/contentassets/0ec2594f7dea45b8b1dec0c44a0133b4/report-carbon-footprint-norwegian-seafood-products-2017_final_120220.pdf

Woods, J. S., Veltman, K., Huijbregts, M. A., Verones, F., & Hertwich, E. G. (2016). Towards a meaningful assessment of marine ecological impacts in life cycle assessment (LCA). *Environment International*, *89*, 48–61. https://doi.org/10.1016/j.envint.2015.12.033

Ziegler, F., Winther, U., Hognes, E. S., Emanuelsson, A., Sund, V., & Ellingsen, H. (2013). The carbon footprint of Norwegian seafood products on the global seafood market. *Journal of Industrial Ecology*, *17*(1), 103–116. https://doi.org/10.1111/j.1530-9290.2012.00485.x

How to cite this article: Philis G, Ziegler F, Jansen MD, et al. Quantifying environmental impacts of cleaner fish used as sea lice treatments in salmon aquaculture with Life Cycle Assessment. *J Ind Ecol*. 2021;1-14. https://doi.org/10.1111/jiec.13118