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Sustainable aquafeed? The devil is in the detail

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ABSTRACT

Aquaculture is essential to meet the increasing demand for nutritious seafood. Aquafeed input represents most of the environmental impact and production cost, formulations consist of a combination of marine and plant-based ingredients. Driven by economic and sustainability incentives there has been a shift from marine ingredients towards plant-based ingredients, and smaller inclusions of (fish) by-products and novel feed ingredients. We applied Index Decomposition Analysis to assess the changing environmental impact from 2000 to 2020 for the European (European Economic Area (EEA) + United Kingdom (UK)) aquaculture industry. In this period the total production of the main produced species in Europe grew from 1.15 million metric tonnes (MMT) in 2000 to 2.17 MMT in 2020. On an industry level we find a substantial increase in Global warming (314%), Land use (594%), Water consumption (236%), Marine eutrophication (630%) and Freshwater eutrophication (468%), while Wild Fish Use was reduced by 13%. Considering an efficiency metric per kg fish produced, Wild fish use was reduced by 59% while Global warming (103%), Land use (336%), Water consumption (65%), Marine eutrophication (285%) and Freshwater eutrophication (167%) increased substantially. These changes are mostly attributed to the substitution of marine ingredients by plant-based ingredients shifting pressures from marine to terrestrial impacts. While by-product utilisation for marine ingredients contributed to a lower reliance on marine ingredients without significant trade-offs. We demonstrate that use of two terrestrial ingredients, soy protein concentrate, and rapeseed oil, have had a disproportionate and detrimental impact on the environmental footprint, emphasising the need for comprehensive and consistent sustainability assessments of aquafeed and aquaculture production.

1. Introduction

The global demand for seafood has increased due to population growth and increasing consumption per capita, from around 10 kg/capita/year in the 1960s to more than 20.5 kg/capita/year in 2019 (FAO, 2024). Seafood products have a crucial role in the global food system being valuable sources of nutrients essential for healthy diets (FAO, 2024), providing 15% of the global animal protein supply (FAO, 2024), while some are also rich in essential omega-3 fatty acids (eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA)), vitamin D and B12, iodine, selenium, minerals and bioavailable proteins (Aakre et al., 2019; Tacon and Metian, 2018). Aquaculture holds the promise of playing an important role to supply most of the seafood in the future, as capture fisheries are likely to remain stagnant or decline further.

Finfish aquaculture in Europe is dominated by five finfish species, Atlantic salmon (*Salmo salar)*, rainbow trout (*Oncorhynchus mykiss*), gilthead seabream (*Sparus aurata)*, European seabass (*Dicentrarchus labrax)* and common carp (*Cyprinus carpio)* (FAO, 2023). Production volumes of these species combined has increased from 1.15 million metric tonnes (MMT) in 2000 to 2.17 MMT in 2020 (FAO, 2023). This growth has been dominated by expansion of cage-farmed Atlantic salmon, predominantly in Norway (Fig. 1).

While aquaculture products overall tend to have better environmental performance compared to most terrestrial livestock products (Gephart et al., 2021), Life Cycle Assessments (LCAs) find that most of (50–90%) the environmental impact of fed aquaculture production is feed-related (Bohnes et al., 2018; Little et al., 2018). Aquafeed formulations consist of a combination of marine ingredients ((MI), e.g. fishmeal and fish oil), terrestrial ingredients (e.g., soybean meal and rapeseed oil) and recently low inclusions of novel feed ingredients (e.g., microalgae and single cell proteins, comprising 0.4% of the average feed formulation in the Norwegian salmon sector) (Aas et al., 2022; Gephart et al., 2021). While LCA shows the environmental impact of a production system and identifies hotspots within these production systems, such as feed use, it does not explain which factors contribute to the change of environmental impact over time.

The growth in production volumes of these finfish species increased the reliance on (imported) feed ingredients and associated marine and

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terrestrial environmental impact (Newton and Little, 2018). Additionally, from 2000 to 2020 European (EEA + UK) aquaculture has also intensified, with a higher share of farmed production relying on feed (Newton and Little, 2018; Tacon, 2019). While salmon and rainbow trout production rely completely on feed, the share of fed production of gilthead seabream and European seabass increased from 60% to 80%, while fed carp production increased from 37% to 55% (Tacon and Metian, 2015). However, during this time, feed technology and management has improved demonstrated by a reduction in the economic Feed Conversion Ratio (eFCR, the ratio of feed provided to harvested biomass) leading to a reduction in environmental impact (Tacon and Metian, 2015). Simultaneously, the composition of aquafeed has changed. This is mainly due to a steady reduction in the inclusion level of MI in the diet, from virtually the complete feed composition for Atlantic salmon in the 1990s to around 60% in the 2000s to less than a quarter in 2020 (Aas et al., 2022; Kok et al., 2020; Naylor et al., 2009). These MI reached the peak of production in the mid-1990s and were included in large proportions due to their excellent nutritional profiles and digestibility but as aquaculture grew, the supply of MIs could not and have been replaced by plant-based ingredients (PBI) derived mainly from soy, rapeseed, and various cereals (Malcorps et al., 2019; Salin et al., 2018; Shepherd et al., 2017). This shift from MI towards PBI is considered by some as environmentally sustainable because it is perceived as reducing the pressure and dependency on finite marine resources (Naylor et al., 2009). Simultaneously, higher utilisation of fish processing by-products has increased the supply of MIs and has arguably reduced the pressure on wild fish stocks (Kok et al., 2020), but is not likely to keep pace with the growth in aquaculture (Jackson and Newton, 2016). Other studies point out that substitution of MI shifts environmental pressure from the marine to the terrestrial system by posing higher pressures on land resources, increased pollution, and freshwater use (Malcorps et al., 2019; Newton and Little, 2018; Pahlow et al., 2015). Globally, the agricultural system is already under pressure from the increasing demand for food, feed, biofuels, and the effects of climate change (Fry et al., 2016). The majority of suitable agricultural land is occupied (Popp et al., 2017), of which a large fraction (77%) is used for animal production through pastures and indirectly for feed production (Ritchie and Roser, 2019). The global food system is the primary driver of biodiversity loss (Benton et al., 2021), while agriculture activities are also responsible for 70% of global freshwater consumption, potentially contributing to water scarcity (Salin et al., 2018). There are also concerns around the application of fertilizers leading to eutrophication and, consequently, dead zones in coastal marine ecosystems (Pelletier et al., 2018).

The relative impact of changes and improvements in the aquaculture industry on influencing the environmental impact of aquaculture feed production are unknown. Therefore, this study aims to address this knowledge gap and demonstrate the use of decomposition analysis to contribute to the understanding how the change in environmental impact between 2000 and 2020 can be attributed to various factors. For this, we used a retrospective Index Decomposition Analysis (IDA), a group of analytical methods originally applied to quantify the impacts of structural shifts and sectoral energy demand (Ang and Zhang, 2000). Since then, decomposition analysis has been used to explain and quantify the driving factors of CO_2 emission, environmental management, and natural resources trends (Ang and Zhang, 2000). In agricultural systems, decomposition analysis has been used in a few studies to asses effects such as; the impact of energy systems on greenhouse gas (GHG) emissions of European agriculture (Peng et al., 2024), and GHG emission intensity of food production systems in Europe and Nigeria (Mrówczyńska-Kamińska et al., 2023; Okorie and Lin, 2022). However, no papers were identified where feed or aquaculture were assessed. In this paper, we present a novel application of IDA to analyse the effect of various trends in aquaculture on the environmental impact of commercial aquafeed and apply it to the European aquaculture industry.

In this paper we use IDA to quantify the change in Life Cycle impacts of the aquaculture sector in Europe during its rapid growth in the first two decades of the 21st Century. The environmental impact of the top five finfish species in Europe were calculated for 2000 and 2020 and the different factors causing the changes were disaggregated using IDA focussing on Wild fish use, Global warming, Land use and Water consumption (blue water). Blue water is defined as that which has been abstracted from water bodies or groundwater compared to "green water" which is from precipitation, and "grey water" which is the volume required to assimilate pollutants (Mekonnen and Hoekstra, 2011) and, eutrophication (Marine and Freshwater). The eFIFO metric was applied for Wild fish use for MIs (Kok et al., 2020), and for the other impact categories the GFLI (Global Feed Lifecycle Institute) database (GFLI, 2023) with ReCiPe impact assessment method. Economic allocation in line with the PEFCR (Product Environmental Footprint Category Rules) for feed was used for all impact categories (PEFCR Feed for food producing animals, 2018). While all these impact categories are, or could potentially be, included within LCA, an LCA tends to only show a specific time point. Changes over time can be measured with LCA by assessing the system at two different time points. However, this is often limited in interpretation as to why the footprint changed. It might become apparent that the contribution of plant ingredients increased due to feed formulation changes, but at the same time there are other factors that may have decreased the contribution of the same ingredients, for example the eFCR. This makes it difficult to definitively state which factor had which effect on the total footprint. Decomposition analysis disaggregates the differences in footprint by analysing specific "effects" on the system model which provides more insightful interpretation than LCA alone. Therefore, we aim to demonstrate IDA as a useful addition to LCA interpretation to better quantify how impacts change due to long term trends.

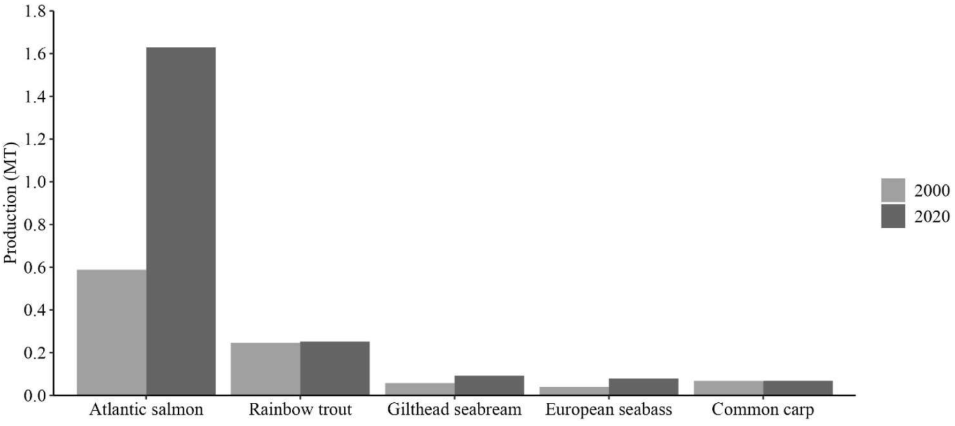

Fig. 1. *Production quantity European (EU & EEA) aquaculture species for 2000 and 2020, data from* (FAO, 2023).

2. Methods

In this study the most relevant impacts of aquaculture production are assessed: 1. Wild fish use 2. Global warming 3. Land use 4. Water consumption 5. Marine eutrophication 6. Freshwater eutrophication. The environmental impact per tonne of feed (EIF) is dependent on the environment impact per tonne ingredient multiplied by the amount of that ingredient included in the feed formulation. The mathematical formulation from Malcorps et al. (2019) is shown in equation (1).

$$EIF_{C,S} = \sum_{I} \left(IF_{I,S} {}^{*} \, EI_{C,I} \right) \qquad \text{(Equation1)}$$

Where:

$EIF_{S,C}$: Environmental impact of feed for species S on Impact category C.

$IF_{I,S}$: Ingredient Fraction (%) of ingredient I for species S.

$EI_{C,I}$: Environmental impact of ingredient I on category C.

However, different aquaculture species not only differ in their feed composition but also in their eFCR. Consequently, the environmental impact of the feed consumed by the European aquaculture industry is dependent on the impact of the feed multiplied by the amount of feed used. Combining Equation (1) with the eFCR gives the following formula for the environmental impact of a species (EIS) of environmental impact category C for species S:

$$EIS_{C,S} = eFCR_s {}^{*} EIF_{R,S} = eFCR_s {}^{*} \sum_{I} \left(IF_{I,S} {}^{*} \, EI_{C,I} \right) \qquad \text{(Equation 2)}$$

Where:

$eFCR_S$: Economic feed conversion ratio of species S.

The total environmental impact can then be calculated by multiplying the footprint of the feed for each species with the volume of production using this feed, which is a combination of the total production volume and the fraction of this production that relies on the use of feed. This gives the following formula to calculate the total environmental impact (TEI) of the European aquaculture industry:

$$TEI_C = \sum_{s} \left[V_s {}^{*} \%Fed_s {}^{*} eFCR_s {}^{*} \sum_{I} \left(IF_{I,S} {}^{*} \, EI_{C,I} \right) \right] \qquad \text{(Equation3)}$$

TEI_C = Total Environmental Impact on category C.

V_S = Production volume of species S.

$\%Fed_S$ = Volume of species S that is produced with feed.

2.1. IDA

For the IDA, the framework of Ang (2015) was applied. Following the Log mean divisia index (LMDI) method equation (3) can be rewritten to define the parameters of the decomposition (Equations (4) and (4b)). A separate decomposition identity was formulated for Wild fish used to distinguish the impact of improved by-product utilisation, shown as equation (4b).

$$TEI_C = V {}^{*} \Sigma_s \left[\frac{V_S}{V} {}^{*} \frac{Fed_S}{V_S} {}^{*} \Sigma \left[\frac{Feed_S}{Fed_S} {}^{*} \Sigma_I \left(\frac{I_I}{Feeds} {}^{*} \frac{EI_{I,C}}{I_I} \right) \right] \right] \qquad \text{(Equation 4)}$$

$$TEI_{Fish} = V {}^{*} \Sigma_s \left[\frac{V_S}{V} {}^{*} \frac{Fed_S}{V_S} {}^{*} \Sigma \left[\frac{Feed_S}{Fed_S} {}^{*} \Sigma_I \left(\frac{I_I}{Feeds} {}^{*} \frac{WF_I}{I_I} {}^{*} \frac{EI_{Fish,I}}{WF_I} \right) \right] \right] \qquad \text{(Equation 4b)}$$

Where:

TEI_C = Total Environmental Impact on impact category C, in equation (4b) fish for impact on Wild fish use.

V = Total production volume

V_S = Production volume of species S.

Fed_S = Volume of species S that is produced with feed (%Feds * Vs).

$Feed_s$ = Feed needed to produce the volume produced with feed (Fed_s *eFCR).

I_I = Volume of ingredient I in the feed (IF_I*$Feed_s$).

$EI_{I,C}$ = Environmental impact of impact of the production of ingredient I on impact category C.

And for equation (1b):

WF_I = Amount of ingredient I from Wild fish (1-byproducts).

$EI_{Fish,\ I}$ = Wild fish embodied in ingredient I.

In this decomposition identity, the effects shown in equation 5 (a-d) and 6 (a-g) (for the Wild fish use) can be found. First there is a volume effect (a) second there are several structure effects, a species structure effect of the relative production volumes of the different farmed species (b), feed composition effect (e), and the intensity effect of feed conversion efficiency (d). In addition, specifically for Wild fish use there is the addition of the intensity effect of by-product utilisation (6e), and an ingredient production intensity effect (6f).

$$V^T = \sum V_s \qquad \text{(Equation 5a: Volume effect)}$$

$$S_{sp.}{}^T = \frac{V_s}{V} \qquad \text{(Equation 5b: Species structure effect)}$$

$$Fed_{sp.}{}^T = \frac{Fed_s}{V_s} \qquad \text{(Equation 5c: Intensity effect)}$$

$$I_{FC}{}^T = \frac{Feed_S}{Fed_S} \qquad \text{(Equation 5d: Feed conversion intensity)}$$

$$S_{feed}{}^T = \frac{I_I}{Feeds} \qquad \text{(Equation 5e: Feed composition structure)}$$

$$I_{Ingr.}{}^T = \frac{EI_{I,C}}{I_I} \qquad \text{(Equation 5f: Ingredient production resource intensity)}$$

For the Wild fish use (Equation (6)), the addition of the by-product utilisation effect is given by Equation 6 f-g:Wild fish

$$V^T = \sum V_s \qquad \text{(Equation 6a: Volume effect)}$$

$$S_{sp.}{}^T = \frac{V_s}{V} \qquad \text{(Equation 6b: Species structure effect)}$$

$$Fed_{sp.}{}^T = \frac{Fed_s}{V_s} \qquad \text{(Equation 6c: Intensity effect)}$$

$$I_{FC}{}^T = \frac{Feed_S}{Fed_S} \qquad \text{(Equation 6d: Feed conversion intensity)}$$

$$S_{feed}{}^T = \frac{I_I}{Feeds} \qquad \text{(Equation 6e: Feed composition structure)}$$

$$I_{by-products} = \frac{WF_I}{I_I} \qquad \text{(Equation 6f: By-product utilisation effect)}$$

$$I_{Ingr.}{}^T = \frac{EI_{I,C}}{I_I} \qquad \text{(Equation 6g: Ingredient production resource intensity)}$$

The formula for calculating an effect in the LMDI-I method is $\Sigma L \left(TEI_I{}^T, TEI_I{}^0 \right) ln \left(\frac{A^T}{A^0} \right)$

TEI_C^T = Total Environmental Impact on impact category C, at time point T (2020).

TEI_C^0 = Total Environmental Impact on impact category C, at time point 0 (2000).

$L(x,y)$ being the logarithmic mean $L(x,y) = \frac{x-y}{ln\ (x) - ln\ (y)}$. And A being one of the effects in equation (6) above (Ang, 2016; Ang and Wang, 2015).

In this research zero values occurred as ingredients were not used in one year but were used in the other year of calculation. For example, the Norwegian Atlantic salmon sector did not use soy protein concentrate in

2000 but did use soy protein concentrate in 2020. Zero values also occurred when there was no use of a certain ingredient in either year of calculation. As recommended by Ang and Liu (2007) the small value approach was used where a small value δ substitutes zero values, the small value δ used in this research was $\delta = 10^{-150}$.

2.2. *Species*

For the purpose of this study we selected the five species dominating (by 96%) the EEA aquaculture production volume, namely Atlantic salmon (71%), rainbow trout (13%), gilthead seabream (4%), European seabass (4%), and common carp (3%) (FAO, 2023). The Atlantic salmon industry was split between the Norwegian industry representing approximately 85% of production, and that in the UK representing approximately 12% of the industry which was used as representative of the remainder European production due to differing feed formulations. Rainbow trout was separated between marine and freshwater production which also uses different feed formulations. Production volumes of the five species is shown in Supplementary Information Table 1.

2.3. *Feed formulations*

The composition of most commercial feed is sensitive and not publicly accessible. Therefore, Pahlow et al. (2015) used reference or standard feed formulations that are known to satisfy dietary needs and are commonly used in aquaculture production. This approach was adopted in this research and the feed formulations are shown in Supplementary Information Table 2a and b.

2.4. *Environmental impact of aquafeed ingredients*

The environmental impact of feed ingredients was obtained from the GFLI database using the ReCiPe impact assessment method (ReCiPe 2016 midpoint (H)) (GFLI, 2023). In this study, economic allocation was applied as the most appropriate allocation method. This is in line with the recommendations in the “PEFCR feed for food production animal”, which stated that economic allocation is the most appropriate allocation method and has several advantages over mass and energy allocation (PEFCR Feed for food producing animals, 2018).

Allocation of impacts between co-products resulting from a single process is an important consideration, especially regarding feed ingredients which are often produced from multi-output processes. For example, in regards to terrestrial feed ingredients, rapeseed is processed into rapeseed oil and rapeseed meal. Some argue that allocation should be according to relative mass (Ayer et al., 2007; Parker, 2018). However, using mass allocation gives an identical footprint (per kg product) to all outputs of a multi-functional process. Many argue that impacts from by-products should not be allocated in the same way, particularly when they have a low utility or cause waste streams and incentives are required to drive better utilisation (Kok et al., 2020). Allocation based on economic value results in low value by-products carrying relatively lower environmental impacts and therefore an incentive is provided to their use from a sustainability perspective. We therefore used the GFLI v2 economic database, ReCiPe impact factors (GFLI, 2023) for the environmental impact of ingredients used in the feed formulations. The mapping of feed ingredients to theGFLI database are shown in supplementary methods table 3.

Some feed ingredients are not available in the GFLI database, most notably guar meal in Norwegian salmon feed. Therefore, the share of guar meal was distributed over the other available vegetable protein ingredients. Feed ingredients for which LCI data were not available, with a share of <1% of diet formulation were distributed evenly over all ingredients.

3. Results

3.1. *Total change in environmental impact of aquafeed for Europe*

Changes in environmental impact associated with feed use during this time are shown in Fig. 2, including use of Wild fish, Global warming, Land use, Water consumption and Marine and Freshwater eutrophication. Overall, the environmental impact of aquaculture feed production has become more severe over time, shown in the red bars of Fig. 2. While the use of wild fish as feed has decreased (−13%) (Fig. 2a), this reduction was overshadowed by substantial increases in other environmental impacts. For instance, Global warming increased from 1.29 to 5.33 MT carbon dioxide equivalent (+314%) (Fig. 1b), and Land use increased from 1389 to 9644 square kilometres (+594%) (Fig. 1c). Similarly, Water consumption (236%) and Eutrophication increased substantially with 630% and 468% for Marine and Freshwater eutrophication respectively.

3.2. *Disaggregation of total change*

This observed change in environmental impact was disaggregated using the IDA, shown in Fig. 3. The total net change between 2000 and 2020, shown in the green and red bars in Fig. 2 and red diamonds of Fig. 3, is broken down into different drivers. The significant growth in the European aquaculture industry from 1.15 to 2.17 million tonnes (+89%) would have caused a substantial increase across the impact categories (Fig. 3a-f, Volume). This growth of the industry would have increased in wild fish demand of 1.75 million tonnes. However, MI inclusion in feed formulation has been reduced in the same period which has led to a decreased impact on marine fisheries from European aquaculture (1.5 million tonnes) (Fig. 3a, feed composition). Simultaneously an increase in fishery by-product utilisation as raw material for MI has further reduced the use of wild fish by 0.8 million tonnes (Fig. 3a) resulting in an overall reduction from 2.6 to 2.3 million tonnes (−13%). The rise in Land use can be attributed partially to the expansion of aquaculture production (743 km^{2}a crop eq.), while the majority can be attributed to the substitution of MI with PBI, resulting in a Land use increase of 7519 km^{2}a crop eq. For Global warming including Land Use Change (LUC) (Fig. 3b) the effect of higher aquaculture production causes a stronger increase of 0.96 MT CO$_{2eq}$ between 2000 and 2020. The effect of changes in feed composition over this period is much stronger with 3.1 MT CO$_{2eq}$. Water consumption, Marine eutrophication and, Freshwater eutrophication (Fig. 3d–f) follow similar patterns with substantial increases caused by the growth of the industry but much more significant increases being caused by the change in feed formulation. Other factors such as the relative proportion of species produced in Europe (structure), eFCR and the proportion of fed aquaculture (% fed) have negligible effects on all impact categories (Fig. 3).

3.3. *Change in efficiency of aquaculture*

The efficiency of aquaculture as measured in environmental footprint per kg of fish produced has also changed substantially. In 2000 the average eFIFO ratio of the assessed species was 2.6 kg Wild fish/kg fish produced which declined to 1.1 kg Wild fish/kg fish produced by 2020, a decrease of 59%. Simultaneously, the increase in terrestrial impacts has been dramatic as shown in Fig. 4. The average Global warming increased from 1.24 to 2.55 CO$_{2eq}$/kg fish produced (+106%) and Land use from 1.04 to 4.55 m^{2}a crop eq/kg fish produced (+336%). This shift is most prominent in the Norwegian salmon industry where the reduction of MI inclusion has been relatively more pronounced (57.5% inclusion in 2000 to 30.7% in 2020). As Atlantic salmon aquaculture in Norway is the largest producer within European aquaculture, this has a strong effect on the European average.

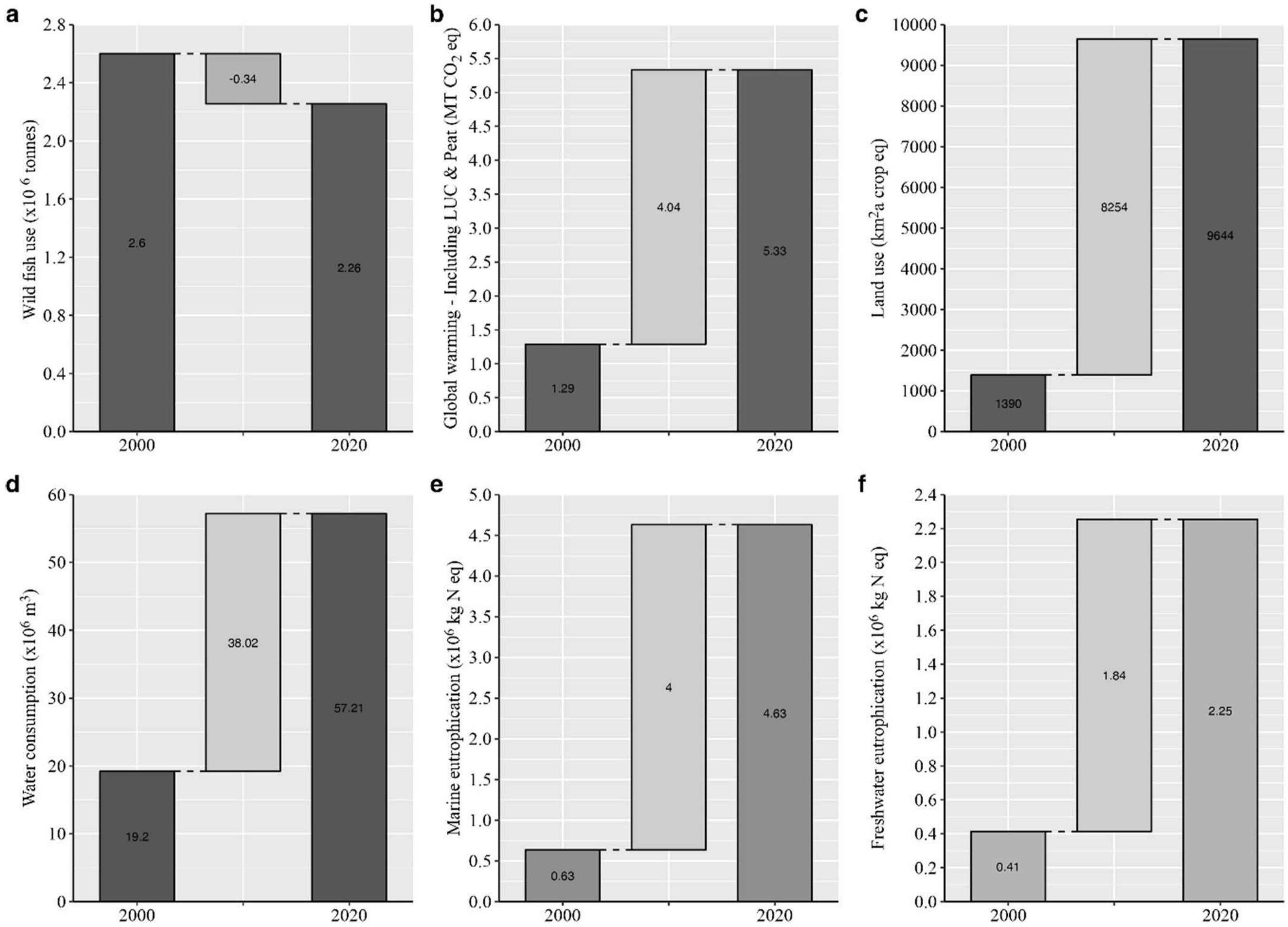

Fig. 2. a–f: Changes in environmental impact of feed for European aquaculture species between 2000 and 2020. Red bars show the net change between 2000 and 2020, which is disaggregated in Fig. 3a–f. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.4. *Effect of feed composition*

The effect of feed composition changes (Fig. 3, Feed composition) was further disaggregated to the individual ingredients and aquaculture species (Fig. 5a–f). Reduced inclusion of fishmeal and fish oil resulted in a little more than 1.1 million tonnes and 0.4 million tonnes less used in European aquaculture in 2020. This demonstrates that the effort of the aquaculture industry to reduce its impact on marine resources has been tremendously effective as total use of wild fish has reduced while nearly doubling production. Simultaneously the reduction in MI use has a negative contribution in the other impact categories, for example Global warming decreases less than 0.5 MT CO_{2eq}. but is outweighed by negative contributions from other ingredients. The increase in the other environmental impacts from changing feed composition (Fig. 5b–f) is largely the result of the inclusion of soy protein concentrate (SPC) and rapeseed oil. The contribution to Global warming of these two ingredients has increased by 2.3 and 0.6 MT CO_{2eq}., respectively, even though they represent only around 20% each of the Norwegian salmon feed inclusion. Similar results are shown for Land use (Fig. 5c), Marine and Freshwater eutrophication (Fig. 5e and f). For Water consumption the use of wheat gluten has had a more significant impact while rapeseed oil has a relatively lower impact.

3.5. *By-product utilisation*

Over the past two decades, the utilisation of fish by-products to produce MI has increased. This has resulted in substantial reduction in Wild fish use (−0.85 MT) (Fig. 3a, orange), which has been further disaggregated into the contribution of by-product utilisation for different species (Fig. 6). In this case no data was available for the share of FM and FO from by-products in the feed formulation specifically for each species, therefore the contribution reflects the global average of the volume of FM and FO coming from by-products used by the various species at approximately 33% of FM and 26% of FO derived from by-products in 2020 (Jackson and Newton, 2016).

4. Discussion

We aimed to better quantify the changing environmental impact of European aquaculture from 2000 to 2020 due to changing practices and expansion. The near doubling of European aquaculture production in the last two decades together with changes in feed composition increased overall environmental footprint by a factor of between 3 and 7 depending on impact category. The substitution of MI with plant-based ingredients has been a great success in that it has allowed the European aquaculture industry to grow while simultaneously reducing overall pressures on fisheries stocks in the face of continued negative public attention on this one issue. However, this has led to unpredicted and unwelcome impacts on terrestrial systems. This can be explained by the increased share of soy protein concentrates and rapeseed oil as highly intensive feed ingredients (Boissy et al., 2011) compared to MI which typically have an overall lower environmental impact for Global warming and terrestrial impacts (Newton et al., 2023). We found that the Global warming of salmon feed increased from 1.5 to 3 and 1.6 kg

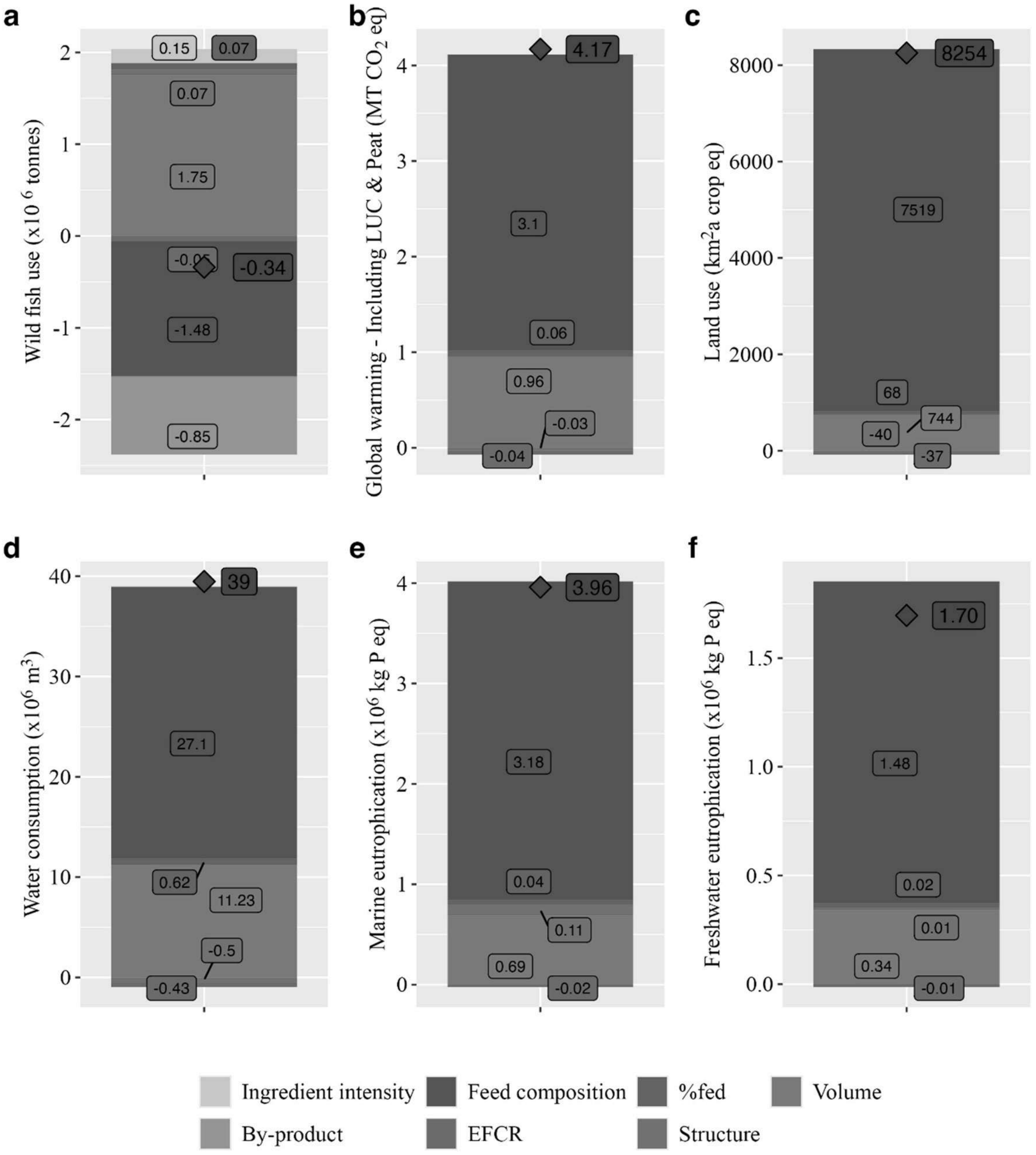

Fig. 3. a–f: Changes in environmental impact for feed for European aquaculture species between 2000 and 2020. Net change (red diamond) is the net change (green or red bar) shown in Fig. 2. Volume shows the effect of only an increase in total aquaculture production, feed composition shows the effect of changes in the raw material composition of the feed, structure shows the effect of relative production of different species, %fed shows the effect of the share of the species that are produced in fed aquaculture systems, eFCR shows the effect of changes in feed conversion efficiency, by-products shows the effect of changes in by-product utilisation for the production of marine ingredients, ingredient intensity shows the effect of changes in the footprint of ingredient production, in this study this is only available for the Wild fish use in marine ingredients and is an effect from shifting allocation towards fish oil in the eFIFO method.

CO_{2eq}/kg fish produced for Norwegian and Scottish production respectively over the last two decades with current figures being comparable with footprints reported elsewhere (MacLeod et al., 2019). The difference between the two can be explained largely due to the much higher inclusion of fishmeal and fish oil in the feed formulation of Scottish salmon production (MacLeod et al., 2019; Aas et al., 2022). Pahlow et al. (2015) demonstrated similar relative increases in water footprint. Malcorps et al. (2019) similarly found that the replacement of marine ingredients had strong trade-offs in terrestrial impacts for shrimp production. In this paper we provide an average of the total industry. The raw materials and especially sourcing of raw materials differs between feed producers. This is especially relevant for soy based raw materials where sourcing heavily influences the raw material footprint due to sourcing of soy from farms that can prove they do not contribute to Land Use Change.

The effect of species structure, intensification, and feed efficiency (eFCR) are negligible. The small effect of intensification can be explained by the fact that of the species studied, intensification only increased a small amount in European seabass, gilthead seabream and common carp which have a relatively small contribution to the total European aquaculture production, while salmon and trout farming, were fully intensified for the entire period (Tacon and Metian, 2015). Similarly, the eFCR of salmon production has remained the same in the period considered, while the improvements to eFCR in the other species

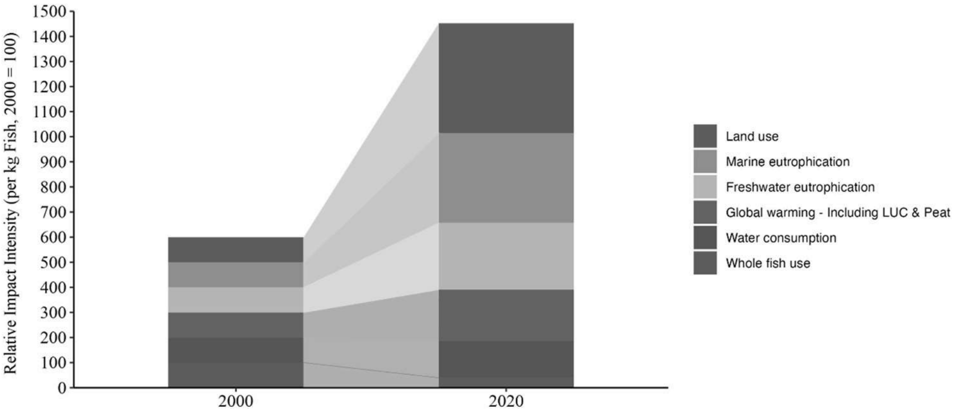

Fig. 4. Changes in average environmental impact for feed for European aquaculture species per kg fish produced. Environmental impact per impact category in 2000 is 100.

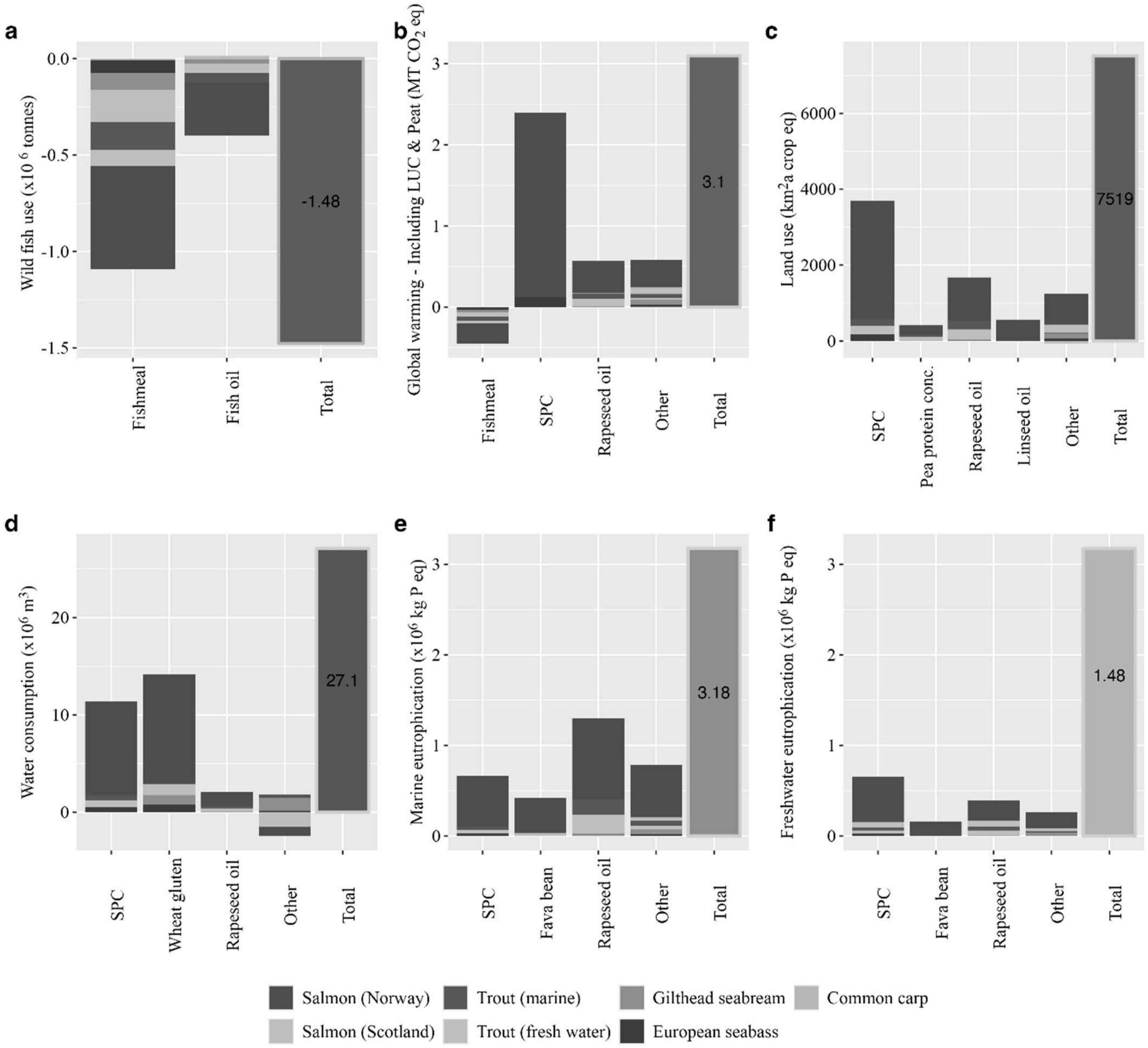

Fig. 5. a–f. Disaggregation of the feed composition effect for European aquaculture species. Totals presented in the are the same as Fig. 3a–f, feed composition.

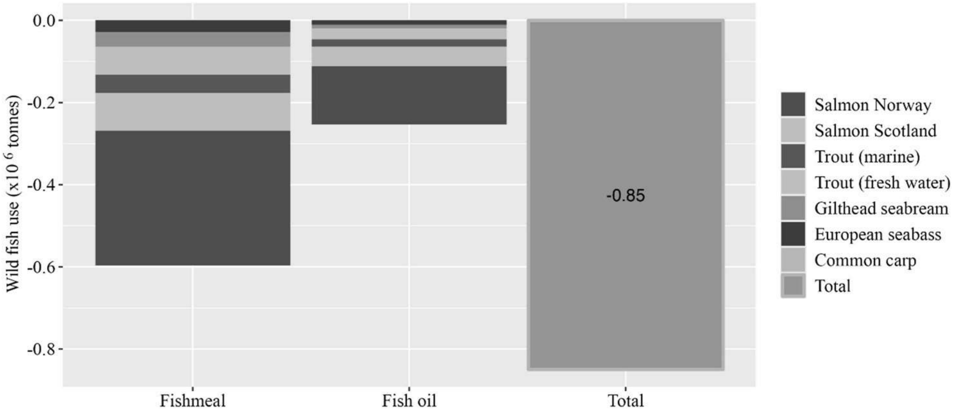

Fig. 6. *Disaggregation of the effect of fisheries by-product inclusion for European* aquaculture species. *Total refers to* Fig. 1a*, by-product. Total is the same as* Fig. 3a*, by-product utilisation.*

considered have only had a minor effect. This is in marked contrast to the rapid improvements in broiler chicken eFCR (Kuempel et al., 2023).

While quantification of environmental impact is an essential part of sustainability assessment, they must be contextualised against factors such as the relative state of resources (e.g., health of fish stocks, impact of deforestation on biodiversity), and are practices part of traceability, and certification schemes for example. I.e. do these impacts have significant consequence overall.

4.1. By-product utilisation

Farmed fish and particularly salmon are marketed for their long chain omega-3 fatty acid (LC n-3 FA) content which can only be obtained through marine ingredients, or novel feed ingredients such as algae to lesser extend, inclusion in its feed. In the face of full exploitation of wild feed fish, it is crucial to further optimise the utilisation of marine resources through the utilisation of processing by-products for marine ingredient production (Newton et al., 2023, 2025; Stevens et al., 2018; Willer et al., 2024). Such by products have lower demand for direct human consumption and are generally considered to have lower environmental impact, even though they are high in nutritional content (especially LC n-3 FAs) and make valuable contributions to feeds (Newton et al., 2025). Although the use of fish by-products in aquafeeds has increased (Jackson and Newton, 2016), many factors contribute to inefficient use or wasting of processing by-products (Malcorps et al., 2021; Stevens et al., 2018). This study demonstrates that using more processing by-products as part of overall MI inclusion does not have significant trade-offs in other environmental impacts, making this a more sustainable pathway.

The concept of by-product use demonstrated in this study could be positively extended to the greater use of terrestrial by-products in aquafeed, although trade-offs in their use for other applications such as livestock feed maybe a constraint. For example, brewers spent grains and rapeseed cake, are already used in livestock feed and could be used in aquaculture (Albrektsen et al., 2022). The over-reliance on unsustainable sourced imported soy and rapeseed has increased pressure on formulators to find local and sustainable alternatives. Similarly, poultry and some other livestock by-products are legal, low cost, low impact and nutritious feed ingredients for aquaculture. They are commonly used outside of Europe, including in fish species commonly imported to Europe, but are not widely used within Europe because of retailer resistance linked to perceptions around consumer acceptance (Regueiro et al., 2021).

4.2. Sustainable future pathways?

Nowadays there is an increasing number of novel and alternative ingredients on the market, each of which need to be assessed for their sustainability credentials. While some show potential to be included in fish diets, some challenges remain such as consistency of quality, quantities, and price (Pelletier et al., 2018). While the current environmental impact of novel and alternative feed ingredients such as algae oil (McKuin et al., 2022), bacterial protein, insect meal (Maiolo et al., 2020; Smetana et al., 2019), has been disappointing, lack of industrial scale production and a reliance on fossil fuel energy largely prevent improved environmental performance compared to conventional ingredients.

Currently similar trends that have pushed the substitution of MI by soy and rapeseed are leading to increased incorporation of these novel feed ingredients in aquaculture production. The considerable trade-offs between impact categories, as demonstrated in this study, must be considered in decision making. The identification and quantification of these environmental sustainability trade-offs requires strong analytical models such as LCA and IDA.

4.3. Contribution to methods

This study demonstrates that IDA can contribute to a better understanding of changing environmental impact of aquaculture and animal production systems. This compliments other assessment tools such as LCA and Value Chain Analysis (VCA). While LCA is useful to identify hotspots and whether a change to a system has or could result in in a reduction or increase in environmental impact it is near impossible to untangle the web of multiple factors that lead to overall environmental impact. This study demonstrates that the use of IDA can untangle these different factors and support data driven policy decisions.

For meaningful application of quantitative analysis methods such as IDA, LCA and VCA, it is important that the methods used are consistent. Due to the differences in impact assessment method the exact environmental impacts are difficult to compare between studies. For example, the water footprint in Pahlow et al. (2015) was assessed using Water consumption weighted by the scarcity of water in the geography it is consumed in and, included grey and green water. In comparison the ReCiPe impact assessment method bases Water consumption on only blue water without weighting. Land use comparisons have similar issues; for example, ReCiPe assesses the occupation of land as well as transformation of land whereas the CML impact assessment method only considers occupation of land as “Land use”. This is particularly relevant for feed ingredients derived from crops with high associated land clearance and transformation such as soy.

4.4. Limitations

In this study, the environmental impact of feed ingredients from the

GFLI database (GFLI, 2023) were used; however, for MI this database does not differentiate between all species, and region and season of origin (Kok et al., 2020; Newton et al., 2023). However, the average Norwegian fishmeal and fish oil in GFLI used in this study has a similar footprint to that found for a variety of fisheries as detailed in the study of Newton et al. (2023). The GFLI database also does not support changes over time, and it is likely that improvements in production processes and yield have resulted in a reduction in environmental impact over time for many ingredients and processes. Although, this study potentially underestimates the environmental impact in 2000 as improvements in the production of raw materials for feed are not considered. This does not influence the observed effect of the factors assessed in this study or the overall conclusions but rather would show an additional effect that would explain the specific consequence of changing footprints of the individual raw materials. For further studies it is important to consider the quality and representativeness of the data and the aim of the study.

While the application of economic allocation is often the preferred allocation method, especially regarding feed use, it also has some shortcomings. Most importantly, temporal and geographical economic volatility, affecting the way environmental impact is reported that can obscure changes in environmental impact (Guinée et al., 2004). The GFLI database therefore uses long term averages for economic value.

Contrary to many industries, food production industries do not have a strong practice of data publication. Although aquaculture production statistics are available from the FAO, these do not cover feed use and feed composition as this is highly sensitive commercial data. Therefore, feed use, and feed composition data were obtained from LCA studies. Given that feed compositions are most often formulated to fulfil the nutritional requirements of the farmed species at the lowest cost (Pahlow et al., 2015), we considered these to be representative for the goal of this study to show the general trends and magnitude of changes in the European aquaculture industry.

5. Conclusion

In conclusion, the substitution of MI with PBI to date cannot be considered a sustainable transition without proper assessment and has resulted in significant environmental trade-offs. There are questions that need to be raised about paying more attention to terrestrial systems and a range of impacts rather than an overused assumption that marine ingredients are unsustainable.

Minimising pressures on both marine and terrestrial environments demands a strong quantitative and qualitative assessment of trade-offs, both known and often-overlooked unknowns. In this sense, the devil is truly in the detail. This study highlights how two terrestrial ingredients, soy protein concentrate, and rapeseed oil, both regarded as sustainable alternatives, have had a disproportionate and detrimental impact on the environmental footprint. Additionally, while novel feed ingredients are often celebrated for their sustainability potential, their environmental performance often falls short of expectations. This is mostly based on relatively small-scale production giving ample space for improvements. These insights point to the need for a careful re-evaluation of feed formulation R&D priorities.

CRediT authorship contribution statement

Björn Kok: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Wesley Malcorps:** Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization, Methodology. **Maria J. Santos:** Writing – review & editing. **Richard W. Newton:** Writing – review & editing, Supervision. **Robert Harmsen:** Writing – review & editing, Supervision, Methodology. **David C. Little:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2026.147666.

Data availability

Data will be made available on request.

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