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Codotto, Giovanni; Pizzol, Massimo; Hegland, Troels Jacob; Madsen, Niels

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Abstract:	Results from Life Cycle Assessment (LCA) studies are sensitive to modelling choices and data used in building the underlying model. This is also relevant for the case of fisheries and LCAs of fish products. Fisheries product systems show both multifunctionality because of simultaneous co-catch of multiple species and potential constraints to supply due to natural stocks limits or socially established limits such as quota systems. The performance of fisheries also varies across seasons, locations, vessels, and target species. In this study we investigate the combined effect of modelling choices and variability on the uncertainty of results of LCA of fish products. We use time series data from official Danish statistics for catch and fuel use of several fisheries disaggregated using a top-down procedure. We apply multiple modelling approaches with different assumptions regarding the type of partitioning, substitution, and constraints. The analysis demonstrates that, in the presence of relevant multifunctionality, the results are substantially affected by the modelling approach chosen. These findings are robust across years and fisheries, indicating that modelling choices contribute to uncertainty more than the variability in fishing conditions. We stress the need for a more careful alignment of research questions and methods for LCA studies of fisheries and recommend a very transparent statement of assumptions, combined with uncertainty and sensitivity analysis.

Model uncertainty versus variability in the life cycle assessment of commercial fisheries

Giovanni Codotto[1], Massimo Pizzol[1]*, Troels Jacob Hegland[2], Niels Madsen[3]

[1] Danish Centre for Environmental Assessment, Department of Sustainability and Planning, Aalborg University, Aalborg, Denmark.

[2] Centre for Blue Governance, Department of Sustainability and Planning, Aalborg University, Aalborg, Denmark.

[3] Environmental Biology Monitoring group, Department of Chemistry and Bioscience, Aalborg University, Aalborg, Denmark.

*Rendsburggade 14, 90000 Aalborg, Denmark. massimo@plan.aau.dk

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Abstract

Results from Life Cycle Assessment (LCA) studies are sensitive to modelling choices and data used in building the underlying model. This is also relevant for the case of fisheries and LCAs of fish products. Fisheries product systems show both multifunctionality because of simultaneous co-catch of multiple species and potential constraints to supply due to natural stocks limits or socially established limits such as quota systems. The performance of fisheries also varies across seasons, locations, vessels, and target species. In this study we investigate the combined effect of modelling choices and variability on the uncertainty of results of LCA of fish products. We use time series data from official Danish statistics for catch and fuel use of several fisheries disaggregated using a top-down procedure. We apply multiple modelling approaches with different assumptions regarding the type of partitioning, substitution, and constraints. The analysis demonstrates that, in the presence of relevant multifunctionality, the results are substantially affected by the modelling approach chosen. These findings are robust across years and fisheries, indicating that modelling choices contribute to uncertainty more than the variability in fishing conditions. We stress the need for a more careful alignment of research questions and methods for LCA studies of fisheries and recommend a very transparent statement of assumptions, combined with uncertainty and sensitivity analysis.

1. INTRODUCTION

There is growing attention to indicators of environmental performance of food products, including carbon footprint. Consumers are increasingly demanding sustainable products and producers rely on Life Cycle Assessment (LCA) among the tools to evaluate performance. However, in contrast to standard voluntary environmental labels, LCA results are not the outcome of a checklist of measurements but the outcome of a modelling exercise. While the use of quantitative indicators based on the results of LCA models can give the impression of high accuracy, the estimates are obtained from a series of subjective modelling choices and present varying degrees of uncertainty.

High sensitivity to assumptions and high uncertainty represent recognized problems with models used for decision making in the sustainability domain (Saltelli et al., 2020). Within the context of LCA it is well-known that modelling choices can substantially affect the results (Lo Piano & Benini, 2022), particularly when using different approaches to the solving of multifunctionality and to the definition of supply mixes. The influence of modelling choices on results has been explored in several studies across different sectors and products such as wood (De Rosa et al., 2018), meat (Wilfart et al., 2021), biorefinery products (Sandin et al., 2015), bioenergy (Brandao et al., 2022; Wardenaar et al., 2012) and fish (Avadí and Fréon 2013), just to mention a few. LCA results can also vary substantially due to intrinsic variability of the processes under analysis. This variability can be related to differences in the performance of production activities across time and space and affects some activities more than others (AzariJafari et al., 2018; Grassauer et al., 2022).

While it is arguably difficult to rigorously classify uncertainty in the context of LCA, various recent studies have attempted this (Brandao et al., 2022; Clavreul et al., 2012; Igos et al., 2019; Lo Piano & Benini, 2022). Generalizing across them, it is possible to divide uncertainty between two main distinct sources: *epistemic* and *aleatory*. For practical purposes, uncertainty due to modelling choices can be defined as epistemic, because it concerns the challenge of using a simplified model to represent a complex reality of which we have only partial knowledge. Other sources of epistemic uncertainty include characterization factors, system boundaries, cut-off criteria, data collection schemes etc. (Henriksson et al., 2015; Hertwich et al., 2008; Huijbregts, 1998; Lloyd & Ries, 2007)

The uncertainty due to the data input to the model can be defined as aleatory because it concerns the challenge of generalizing or providing an instantaneous picture of a process, of which we have limited records, that manifests intrinsic variability. To provide sound decision support a strong focus on the analysis of sources of uncertainty and sensitivity is generally advised in the interpretation of LCA results (Ross et al., 2002; Weidema, 2009).

The product systems of commercial fisheries show both multifunctionality because of simultaneous co-catch of multiple species (Ayer et al., 2006; Bastardie et al., 2022) and potential constraints to supply due to natural stock limits or socially established limits such as quota systems (Froehlich et al., 2018). Moreover, commercial fisheries do not operate in controlled conditions and their performance shows yearly and seasonal variability that translates into uncertainty regarding the estimation of the impact of single fish species or fishing methods.

Since there is not only one univocal way of accounting for the impacts of fisheries in a life cycle perspective, it is key to understand what LCA models align with which questions, and how the choice of model and data can change results and contribute to their uncertainty.

Focusing on epistemic, system modelling-related uncertainties, Ziegler and Hansson (2003) document that the use of mass- or revenue-based allocation considerably change results, up to 31%, and suggest system expansion as most appropriate method, followed by revenue-based allocation, for mixed fisheries. Later, Ayer et al. (2006) conclude their review of problems with co-product allocation LCA of seafood production by proposing allocation based on gross energy content as best alternative but also argues for increased standardization and better justification of allocation choices. Since then, several authors have reported how the allocation choice has major influence on results and these may vary significantly according to co-product allocation method (Avadí & Fréon, 2013; Thrane, 2006). Mogensen et al. (2021) reports large differences between attributional and consequential studies and consider most marine capture fish species as a constrained resource that cannot be increased.

When comparing these two approaches to LCA modeling, as per Avadí & Fréon (2013), the predominant perspective adopted in the field of fisheries is attributional. However, this figure might be outdated, as no more recent reviews of LCA modeling in this specific field could be found.

96 The consequential approach is increasingly being used in the LCA of food products (Schmidt et al., 2021) and it has also been recommended for use in the fishery sector (Vázquez-Rowe & Benetto, 2014). When considering other sources of seafood, such as aquaculture, Philis et al. (2019) report only one consequential study, while according to Bohnes & Laurent (2019) avoiding allocation of aquaculture co-product is very difficult.

Focusing on aleatory, variability-related uncertainties in the input data, Ramos et al. (2011) highlight the need to increase the time frame in order to include in the LCA the strong annual variations of pelagic fisheries. Ramos et al. (2011) also identify high regional variability within Northern-Spain fisheries of small pelagic species and recommend increasing the time frame while paying special attention when reporting national or regional scale results. Ziegler et al. (2018) find considerable variation within the year, but not significant between different years, in a Northeast Atlantic trawl fishery. The variations mentioned can be mainly seen through the variations in fuel consumption, which is highly related not only to the technology factor, such as engine efficiency and fishing techniques, but also to the variation of fish stock status (Bastardie et al., 2022; Ziegler & Hansson, 2003). All these elements combined lead to high variability in fuel consumption in commercial fisheries.

Summing up, the problem of sensitivity to modelling choices has been discussed already in the literature on LCA of fisheries, and LCA results for commercial fisheries are associated with spatial and temporal variations. Previous studies do not explicitly use an uncertainty lens to address the effect of modelling choices and data variability on LCA results for fisheries. Thus, for the case of fisheries, it is currently challenging to draw definitive conclusions regarding the magnitude of uncertainty associated with individual LCA results (e.g. emission of fishing cod in Denmark with a medium-sized trawler). Nonetheless, when considering both epistemic and aleatory sources it is also difficult to define what are the largest contributors to such uncertainty.

The objective of this study is to systematically contrast the epistemic uncertainty due to modelling choices and the intrinsic aleatory uncertainty due to the variability in fishing conditions and vessels. Since LCAs are complex models where modelling and data choices largely drive results, the work here proposed is relevant to identify what are the most critical ones, as well as to provide insights into the size of uncertainty in a specific case. The insights from this study are thus expected to be useful to both researchers in LCA and in fisheries, as well as to stakeholders in the fisheries sector, to better understand and contextualize results from LCA models of commercial fisheries.

2. METHODS

2.1 LCA modelling approaches and methods considered

We distinguish here between modelling approaches, specifically consequential and attributional, and modelling methods, like partitioning and substitution. An approach is here defined as an internally consistent compilation of modelling methods that answer a specific question, while a method is a practical procedure to build a model. Both approaches and methods have been extensively discussed in the LCA literature (Majeau-Bettez et al., 2017; Weidema et al., 2018) and we provide here only a succinct summary of the state of the art.

In short, the consequential approach looks prospectively at the consequences of changes in demand for a product, uses substitution to solve multifunctionality and marginal mixes to model supply (Ekvall & Weidema, 2004) Marginal mixes include only the suppliers that can respond to change in demand and are thus not constrained (Buyle et al., 2018; Weidema et al., 1999). The attributional approach is arguably less strictly defined both in theory and in practice but generally proposes a retrospective tracking of the impacts of a product, uses partitioning to solve multifunctionality, and average mixes to model supply (Ekvall et al., 2016). The LCA community agrees to a good extent that the two modelling approaches should answer different questions and they are thus not directly comparable (Köhler & Pizzol, 2019; Weidema et al., 2018). In practice, however, the choice of one or the other approach and the alignment of this choice with a specific question is most often not clearly motivated, and there are studies that use both approaches (Kua & Kamath, 2014; Smetana et al., 2019).

For fisheries, multifunctionality occurs when a vessel catches multiple species at the same time, a process defined as *co-catch*. In this study, the term co-catch is used in relation to the fish species that are caught, voluntarily or involuntarily, together with the main target species in a specific fishery. Using the partitioning method, the impact of the fishery is split between the target species and the co-catch according to an arbitrary rule, like for example the respective mass or revenue-based value. Since there is no objective way of choosing the rule, this approach requires agreement in industry or across stakeholders, like it is done in the Product Environmental Footprint (*EC*, 2013). This is a relatively intuitive method that is widely used in the literature and solves the multifunctional problem, assuming consensus is reached among the stakeholders - a process that nevertheless has been proven difficult or impossible in some cases, such as the meat industry (Wilfart et al., 2021). Yet, the partitioning method introduces distortions that might impede sound decision support. In fact, the implicit assumption is not only that the demand of one fish co-product will not affect production of the other, but also that each is independent. In the virtual reality of the model, they are produced by two separate and independent activities. Instead, the substitution method assumes that co-catch avoids the production of equivalent fish elsewhere. This method requires a deeper understanding of the primary driver for the fishing activity as well as detailed knowledge of markets for all fish products.

Another key modelling assumption used in the consequential approach is to regard the supply of fish from marine capture as "constrained" by natural limits of the system or socially constructed limitations, often in the shape of quotas. Consequently, an increase in demand for marine capture fish might shift to other, unconstrained suppliers of an equivalent function, for example aquaculture. Overall, at macro level, this assumption might be justified, as global landings of capture fisheries have stabilized from around the 90s while the global production of aquaculture does indeed show an increasing trend (FAO, 2022). On the other hand, this type of model further requires various assumptions about consumer preferences and how they substitute fish with other similar fish or protein sources – assuming one, fully connected and seamless, global market for fish. Therefore, the assumptions might not be applicable at micro level. For example, the response to increases in demand might be nonlinear, so that small increases can be handled within the current carrying capacity of the marine ecosystem and within the current quota system. In that case, the resource will only be constrained in cases of larger changes at macro level. Abandoning this assumption, one would have to make the disclaimer that the model will only be able to reflect small-scale changes in demand.

We apply in this study both the consequential and attributional modelling approach with different but all formally legit assumptions, building up to six different models for each fishery (Table 1). Detailed examples of direct application of these models can be found in the Supporting Information (SI 1.2). Within the attributional approach we perform both mass-based, revenue-based, and energy content-based partitioning. Within the consequential approach we assume both a fully constrained supply of fish from capture fisheries, and unconstrained supply, with either available or not available alternative production routes for the co-products. These models are applied to multiple fisheries considering differences in vessel lengths and fishing years to test the contribution of the variability in fishing conditions to the overall uncertainty.

Table 1. Approaches and methods to model life cycle impacts of fisheries considered in this study.

Approach	Method	Question answered	Assumptions
Attributional	Partitioning by mass (mass allocation)	Retrospective: how can impacts of various activities be attributed to this product based on its mass?	The higher the mass of a product the higher the input needed. Assumes the existence of virtual monofunctional activity
Attributional	Partitioning by revenue (revenue-based allocation)	Retrospective: how can impacts of various activities be attributed to this product based on its revenue?	The higher the revenue of a product the higher the input needed. Assumes the existence of virtual monofunctional activity
Attributional	Partitioning by energy content (energy content allocation)	Retrospective: how can impacts of various activities be attributed to this product, based on its energy content?	The higher the energy content of a product, the higher the input needed. Assumes the existence of virtual monofunctional activity
Consequential	Substitution (Constrained activity)	Prospective: what are the consequences of increasing the demand for this product, when its production cannot be increased due to constraints?	Since production is constrained by quotas, increase in demand will not affect this activity but other ones

Consequential	Substitution (Unconstrained activity, no alternative production routes)	Prospective: what are the consequences of increasing the demand for this product, when it cannot be produced in any other way?	Increasing demand for a product can only be partially met by this activity and the rest is due to other activities
Consequential	Substitution (Unconstrained activity, alternative production routes)	Prospective: what are the consequences of increasing the demand for this product, when there are alternatives in the market?	Increasing demand for a product will be met by this activity, coproducts will substitute alternative production routes in the market

The proposed models are applied to the datasets presented in the following section. To ensure comparability between results, a functional unit is defined as *1 kg of live-weight fish landed*. All results are scaled to this functional unit and calculated with the IPCC 2013 (100a) impact assessment method for the global warming potential (GWP) impact category.

2.2 Sources and processing of data

We consider five vessel lengths of the Danish fisheries: trawlers under 12m, between 15-18m, between 18-24 meters, over 40m and over 40m for industrial fish - based on the aggregation level of fuel data available. Vessels of length 12-15m and 24-40m were excluded from the analysis as the other categories were considered sufficiently representative of the Danish fleet and as data basis for investigating differences across models, which was the main purpose of the study. According to data from Statistics Denmark (statbank.dk), in combination, the fisheries considered in the analysis account for 79% of the total Danish catch in 2019 (about 500,750 tons) and 61% of the total revenue from Danish fisheries (266,6 million EUR). Trawlers over 40 m are generally targeting pelagic fish in the open water column, whereas smaller trawlers are generally targeting demersal resources close to or on the sea floor. Data on these fisheries are available from the central authority on Danish statistics and were retrieved for the years 2017-2019 to study temporal variability. The data were used to derive different LCA models that could return a carbon footprint for different marine capture fish species with a top-down procedure that can be applied systematically. The procedure consists of two steps: disaggregation and then system modelling.

Given the goal of the study, the collection of inputs required in the inventory phase of LCA has been reduced to include only major sources of variability and uncertainty, which are direct expression of fuel consumption. For this reason, the impacts of landing marine capture fish are related only to the fuel consumption of the fishing vessels. This choice is supported by several studies (Avadí & Fréon, 2013; Bastardie et al., 2022; Cortés et al., 2021; Laso et al., 2018;

Thrane, 2006; Ziegler et al., 2013, 2018) that identify fuel consumption up to the landing stage as the main contributor to the carbon footprint of fisheries. Since there is no available data in the official statistics, the potential impact of the practice of discarding fish at sea before landing was not assessed. Nonetheless, all models were applied to the same datasets, ensuring that the comparative results remain consistent.

2.2.1 Disaggregation of Danish statistical data

Disaggregation is here defined as a "top-down" procedure to transform data. It is considered top-down as it takes starting point in the country-level data provided by Statistics Denmark, which aggregate the total catch and fuel consumption for all fisheries of the same vessel lengths in the same year.

Data on the selected vessels included many different fish species. Before performing the disaggregation of fuel consumption, some of these species were grouped together, when considered part of the same fisheries. Data on landed fish were provided for Atlantic cod (Gadus morhua), Haddock (Melanogrammus aeglefinus), Saithe (Pollachius virens) and European hake (Merluccius merluccius). These have been aggregated in the same group of roundfish species, of which Atlantic cod represented between 45 % (Trawlers of 18-24m length) and almost 90% (trawlers below 12 m and of 15-18m length) of total landed mass. European Plaice (Pleuronectes platessa), European Flounder (Platichthys flesus), Witch flounder (Glyptocephalus cynoglossus), Lemon sole (Microstomus kitt), Common sole (Solea solea) and Turbot (Scophthalmus maximus) are aggregated in the same group of flatfish species. Within this group, the amount of landed mass for European Plaice ranged between 56% to around 80% along all the vessel lengths. Given the fact that the above-mentioned species are targeted from the same fishery operations, they have been grouped together in what in the remaining part of the document is referred to as the "roundfish and flatfish" fishery. Data were also available for pelagic species, namely Atlantic herring (*Clupea harengus*), Atlantic mackerel (*Scomber scombrus*), Atlantic horse mackerel (*Trachurus trachurus*), Sprat (*Sprattus sprattus*) and industrial fish. Finally, for the category of crustaceans, landing data is provided for Norway lobster (*Nephrops norvegicus*). For each of the fisheries it is assumed that there is a certain amount of co-catch of industrial fish. In this case, industrial fish refers to all the fish that has been sold for industrial purposes, such as production of fish meal and fish oil, and therefore not used for human consumption.

The composition of the fisheries in terms of amounts of determining product and co-catch have been defined using fishery composition data from Thrane (2004). This data reported in percentages how much of each species could be found in a specific fishery. We disaggregated these data reducing the number of fish categories down to the main ones (Table 2) and determined the total catch and fuel consumption for specific species or sub-groups of fisheries. For example, starting from the generic "Vessels below 12m" category we derived three subcategories of vessels, fishing respectively "Roundfish and flatfish", "Norway lobster" and "Sprat". This might be interpreted as a subset of vessels fishing only these species, or a subset of fishing trips targeting only these species. Once calibrated, the approach is systematic and applicable to data on multiple years and vessel lengths. A detailed breakdown of each fishery category is proposed in Table 2. while the calculation procedures and data sources used in the disaggregation are provided in Supporting Information (SI) 1.1, as well as spreadsheets for reproducing the calculation in SI 2.

Table 2. Disaggregation of vessel length data into sub-categories.

Vessel length (aggregated)	**Target products**

Trawlers below 12m	Roundfish and flatfish Sprat
Trawlers between 15-18m	Roundfish and flatfish Norway lobster Herring Industrial fish
Trawlers between 18-24m	Roundfish and flatfish Norway lobster Herring Industrial fish
Trawlers above 40m	Industrial fish Herring
Industrial trawlers above 40m	Industrial fish

2.3 System modelling with different approaches

Different system modelling approaches were applied to the disaggregated fishery data. We take the Trawlers under 12 m for the year 2019 as an example to explain the various modelling approaches applied. In 2019 this fishery harvested 182 tons of roundfish and 385 tons of flatfish, with the majority of species being Atlantic cod and European plaice. These species were caught together as they to a large extent share the same habitat and seasonal reproductive cycles. 420000 litres of diesel were consumed in the process, equivalent to 1367 CO_2-eq using an emission factor of 3.254 kg CO_2-eq · l^{-1}diesel. Since demersal trawling is species-selective only to a certain level, there is concurrent capture of additional mixed demersal species. Based on the data available, all the fish harvested constitutes a source of revenue for vessels, but roundfish and flatfish are the main sources of revenue as they have the highest share of total revenue. Given the fact that roundfish and flatfish, which are to a large extent covered by quotas, are in this case often caught together, and that there is a ban on discarding of fish species subject to quotas, there is rarely the option to go for either. Nor would that be economically viable for the vessels, which usually depend on a mix of quotas and species to make the fishing operations profitable.

In LCA terms, we can classify this case as *joint production* (Weidema, 2018), as the activity simultaneously produces two product outputs, the volume of whose cannot be varied independently. The technology and intervention matrices for this multifunctional activity with detailed explanation of the models are presented SI 1.2. Moreover, neither of the two products is clearly the determining product (main driver for production) and neither is clearly the dependent one. Additionally, there are different types of constraints affecting the output. One is a policy constraint as the fishing activity is regulated by quotas on both roundfish and flatfish separately. The other constraint is the availability of the natural resource of the fish stocks that, in turn, defines the quotas.

2.3.1 Attributional approach

This approach assumes that the amount of diesel used, and thus the emissions generated, in fishing operations are directly proportional to the quantity of species caught. Thus, the model of the fishing activity is constituted of two (virtual) partitioned fishing activities each producing one of the products. When using the mass-allocational rule, every fish species has the same impact per kg therefore, as a matter of fact, co-products of the same fishery such as roundfish and flatfish have no difference in terms of impacts per kg of product.

The second allocation case is similar, but this time revenue is used instead of mass with very similar allocation factors due to similarity in the prices of the two products. Higher emissions are then allocated to the products that have higher prices, following the logic that higher profit can drive production. The multi-functional activity is here split into two virtual mono-functional activities. In this case the input per unit of mass is not identical between the products and any mass balance between inputs and outputs is lost.

In the third allocation case, emissions are allocated based on the energy content of the products. Similarly to the previous allocation cases, fish products with a higher energy content receive a higher allocation of emissions.

2.3.2 Consequential approach

We considered three possible ways of modelling using the consequential approach depending on assumptions regarding the constraints to supply.

In the first case, the fishery activity is regarded as fully *constrained* and thus not affected by increases in demand. In a cascading effect, the demand is transferred to another marginal activity that is a supplier of a functionally equivalent product and that needs to be identified separately. In this case, farmed rainbow trout (Samuel-Fitwi et al., 2013) is assumed to be the functionally equivalent product, so we assume that the marginal production activity might be an aquaculture activity. Additionally, this could even be modelled as a generic market for proteins. The assumption that the entire capture fishery industry cannot respond to even small increases in demand might be contested and might need to be relaxed. Nonetheless, the problem of separating the two co-products: roundfish and flatfish, remains. Therefore, two further approaches can be used.

The second case is that of an unconstrained activity with no alternative production routes. This happens when neither of the co-products generate sufficient revenue to be considered determining products. Additionally, there are no other unconstrained activities that can produce an equivalent product. In the model, an increase in demand for one co-product leads to an increase in fishing, that only corresponds to the revenue obtainable from this product. In the example we use the same marginal aquaculture activity for both roundfish- and flatfish-equivalent production, but these could be different ones.

The last consequential case is to relax the assumptions even further and identify a determining product and an alternative production route for the co-products. The more co-product is caught by a certain vessel length the less will be supplied by other vessels dedicated to it. This marginal activity might be modelled as an aquaculture activity as in the example below, or even as a generic market for proteins (SI 1.3). This corresponds to the traditional substitution method.

2.3.3 Assumptions regarding substitution

In a consequential model the substitution mechanism, although logic and sound in theory, can be difficult to demonstrate or validate in practice. In this study we made two assumptions to show how the results can change depending on the choice of marginal substitute for fish. We first assume marine capture fish performs the same function (and can be substituted by) farmed rainbow trout, modelled using data from a consequential study on this product (Samuel-Fitwi et al., 2013), so we assume that the marginal activity might be an aquaculture activity. Nonetheless, the consumer might, on average, substitute fish with a variety of products. We thus modelled a generic market for proteins as marginal activity, based on statistics on the average protein consumption in Denmark and removing protein sources that we believe were not intuitively a direct alternative to a fish dish. Details on the calculation and sources for the marginal protein mix are provided in SI 2. A more accurate modelling of consumer preferences was beyond the scope of this study.

2.4 Statistical analysis

To better understand the contribution of each source of uncertainty, we performed Analysis of Variance (ANOVA) and linear regression analysis on the results. We conducted the ANOVA to understand whether different sources of variation namely the type of modelling assumption used (epistemic uncertainty), the trawler length and the year (aleatory uncertainty) lead to significant differences in the value of global warming impact. The regression analysis was used to quantify the contribution of each source, each one represented by a categorical variable. The statistical software R (R Core Team, 2021) was utilized in all cases.

3. RESULTS

Figure 1 shows the results calculated for all fish species groups and LCA models where we highlight the contribution to the uncertainty that is due to the choice of modelling approach (attributional versus consequential, left side) and due to some of the natural variability in fishing practices (vessel length, right side), respectively. The figure conveys how wide the range of potential results that can occur is when every source of uncertainty and variability is combined. We further stress that, while it is practically possible to plot all results on the same chart, the attributional and consequential models are designed to answer different questions and the absolute numerical results should not be compared directly – the reason why they are plotted together is exclusively to compare the uncertainties by the range of potential impacts. Figure 1 shows that the estimates obtained using the attributional approach are closer to each other or have a smaller spread than those obtained using the consequential approach. The overall interpretation of this figure is that neither the epistemic nor the aleatory uncertainties alone can explain the total uncertainty satisfactorily. Looking at each source of uncertainty individually does not reveal any clear pattern, and we therefore consider the two sources of uncertainty in combination.

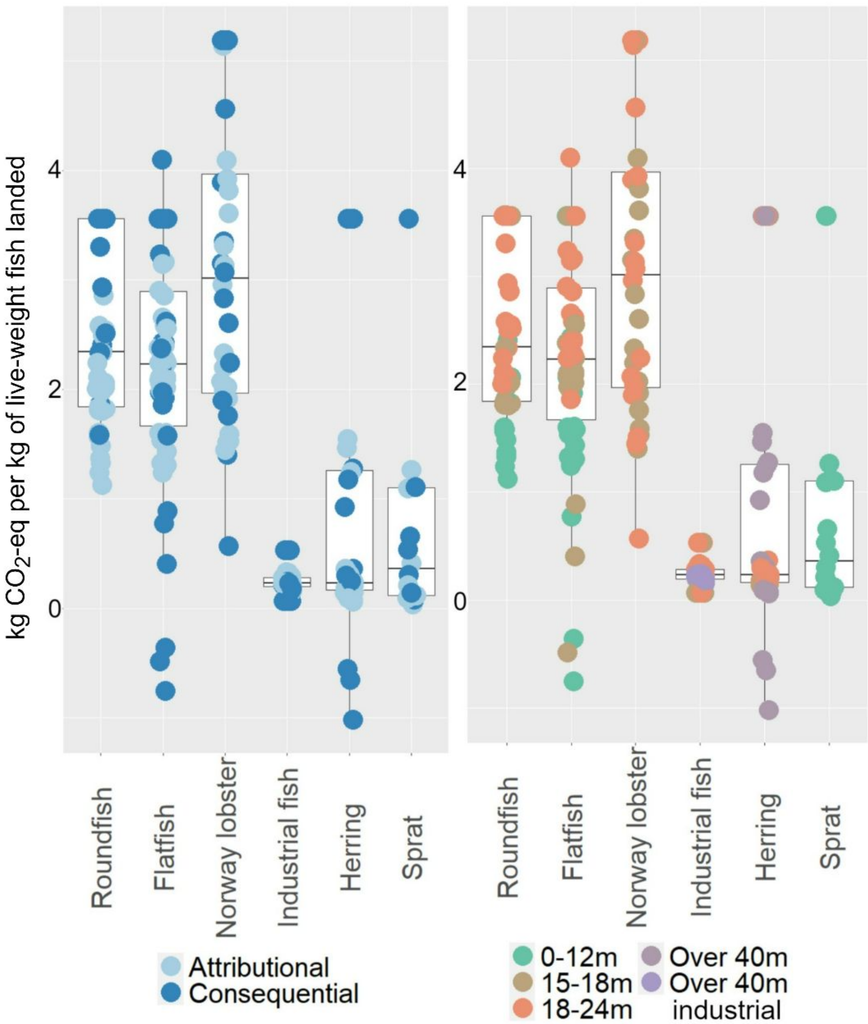

Figure 1. Sum of carbon footprint results obtained for each species according to two modelling approaches, consequential and attributional, on the left, and for different vessel lengths on the right.

Figure 2 presents the same data but further decomposed, where results for the five different system models, two attributional and three consequential, are presented separately in multiple subplots according to vessel length and product under analysis. Within each subplot, replicates indicate measures for different years, showing three data points.

A pattern emerges now and our interpretation of the data is that the uncertainty due to modelling choices is larger than the uncertainty due to temporal variations and to variations in length of vessel. On the other hand, this trend is not equally pronounced for all products. Overall, epistemic uncertainty appears always higher than variability.

Some results obtained with the consequential model present negative values. This is due to the substitution effect in the alternative route consequential model. In fact, if a product is substituted by another product that can be supplied with lower carbon emission, then the emissions from demanding that product comes out negative. In this case we can use the example of the Herring fishery (Figure 2). The Alternative Route model assumes that herring is the main determining product, while the other species from this fishery (mackerel and horse mackerel) are co-catch. For any amount of co-catch landed the production of fish from an alternative source, trout aquaculture in this case, is avoided. As the aquaculture production process has a higher carbon footprint, the net result is negative after subtracting these emissions from the emissions produced by the fishing operation of herring. At the same time co-catch of industrial fish is assumed to avoid its production from the industrial trawlers over 40m, where it is the main product.

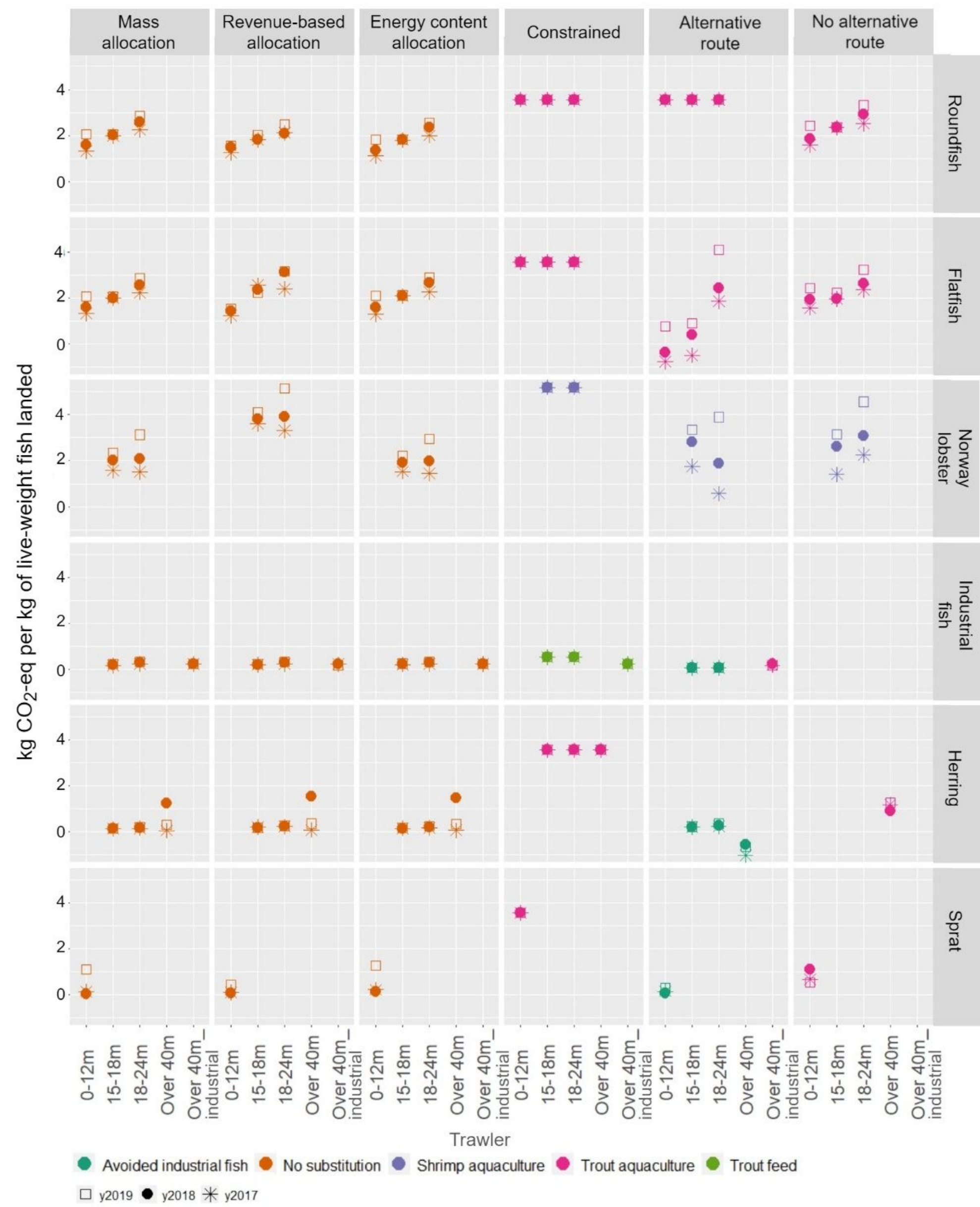

Figure 2. full set of results divided in subplots according to vessel length, species, year and modelling methods. The columns of Alternative Route, Constrained and No alternative route belong to the consequential approach while Revenue-based allocation and Mass allocation belong to the attributional approach. The colors indicate which product substitution is performed within the fishery. Note that in the alternative route scenario substitution is applied only to co-products.

We observe that for single-species fisheries (fisheries with no or low co-catch) the range of results is smaller and there is larger agreement across models. This is because there is either no need to make modelling choices regarding co-catch (such as partitioning or substitution) or because the quantity of co-catch is so low in amount that the effect of assumptions is negligible.

The results of the statistical analysis support the conclusions obtained from the visual analysis improve the understanding of the data and the interpretation of Figure 2 (Full results can be found in SI 2). The ANOVA test revealed that the choice of system model (constrained supply, presence or absence of alternative production route, mass, revenue, or energy allocation) had the most pronounced impact on the observed variance. Even though trawler length emerged as a significant factor affecting variance in roundfish and flatfish, and year for Norway lobster, the differences in variance attributed to the choice of system model were the only ones consistently significant across all species.

The regression analysis indicated that, among the categorical variables, the choice of system model had a greater influence on the results, as evidenced by the highest value of the calculated regression coefficients. Although in specific vessel lengths and years contributed significantly to the variance in impact in some species, the coefficients associated with the year and trawler variables were in general consistently lower than those of the system model by at least one order of magnitude Despite the limited number of variables considered and of data points analysed for each species, the regression models explained rather well the relation between variables and final footprint, with R-squared values between 0.7 and 0.9.

4. DISCUSSION

4.1 The importance of modelling choices in terms of uncertainty

A comparison between uncertainty due to modelling choices and intrinsic variability, across vessel lengths and years, was performed for Danish fisheries. In the context of fisheries, this is the first study to quantitatively compare the two sources of uncertainty.

The results showed that modelling choices introduce an uncertainty that is consistently larger than that due to the variability in fishing conditions. We considered two main modelling approaches of LCA, attributional and consequential, and six respective methods within them, to investigate how well their underlying assumptions represent the complex reality - this is where model uncertainties become relevant. In this study, the attributional approach shows more consistent results compared to the consequential one. This is because the price difference as well as the energy content difference between co-products is minimal, so that the choice of partitioning method does not substantially change results. This specific condition is not easily generalizable to other fisheries where the primary product significantly differs in price compared to the co-catch, such as the case of Norway lobster. The higher the number of outputs of the system, the higher was the effect of the assumption defining the model. This result highlights also how demersal trawl fisheries, identified as mixed-fisheries, are affected by a higher uncertainty compared to pelagic ones, characterized more by single-species. As mentioned before, the multi-functionality of the system needs to be dealt with for any LCA study, which can be considered a challenge not only from an LCA perspective but also for marine governance in terms of stock management (Ulrich et al., 2017).

Modelling choices in life cycle assessment of capture fisheries need therefore to be accounted for and the chosen methods must be as transparent as possible. Besides modelling uncertainties, other sources of uncertainty were analysed as well, among those the temporal variability, variability in species targeted, and vessel length. The contribution to uncertainty due to geographical variability was not assessed. Results confirmed what was found in the literature about temporal variability (Almeida et al., 2014; Ramos et al., 2011), as different years resulted

448 in different carbon footprints due to variations in fuel consumption. Overall, when these factors
449 are compared, uncertainty is dominated by the modelling approach, meaning it is consistently
450 more significative than that for temporal variability or vessel length. On the uncertainty
451 analysis, other approaches are available in the scientific literature on LCA of fish products. For
452 example, Henriksson et al. (2014) aggregates uncertainty and variability together; this is a
453 useful approach to derive a total estimate of uncertainty for the LCA results. However, in this
454 study we needed to maintain them separately to be able to compare them.

455 In the context of LCA, an uncertainty analysis is especially relevant in the communication of
456 results to consumers. For example, the use of oversimplified product labels that only report the
457 numerical result of a complex LCA model, without reporting the uncertainties and the effect
458 of assumptions is problematic, as these labels can give a false impression of accuracy. nAn
459 uncritical and overconfident use of this approach can potentially backfire and ultimately
460 diminish the trust of consumers in LCA studies.

461 *4.2 Considerations on the use of Attributional and Consequential approaches*

462 The attributional approach, both with mass and revenue-based partitioning, is the main
463 approach that can be found across academic literature. The industry has settled around the
464 attributional approach where standards such as the GHG protocol, the Environmental Product
465 Declaration (EPD) as well as the upcoming Product Environmental Footprint (PEF) Category
466 Rules for fish products suggest using it (ISO 14025; Marine Fish PEFCR; WRI, 2014). The
467 market for food is, however, dynamic and influenced by changes in demand so a more realistic
468 picture of the effects induced by changes in consumption can be given by using a consequential
469 approach. The advantage of the consequential approach is that it takes consumers' perspective
470 into account by assessing the consequences of their choices, which is closer to the core purpose
471 of LCA. The consequential model used assumes only one unconstrained supplier of fish:
472 farmed rainbow trout. This choice is made for the sake of simplification, as introducing

multiple potential products as potential substitutions would have complicated the interpretation of results. While it is true that results for the consequential models are highly dependent on this subjective choice, and different unconstrained suppliers would have resulted in different carbon footprints, it does not change the interpretation of the results that model uncertainty is larger than variability.

4.3 Study limitations

Although the study is carried out following the principles of ISO14044 (ISO 14044, 2006), the scope of the assessment was limited to one impact category and one life cycle stage. In this study the models focus entirely on the amount of fuel consumed by commercial fisheries and the resulting carbon emissions, so other potential impacts are excluded from the scope of the analysis. This was a practical and deliberate choice motivated by the fact that the specific objective of the study is to compare variability and uncertainty, so the focus is not on achieving completeness but on narrowing the scope to a limited number of variables. The catch stage that we have included is the most impactful stage in the fisheries sector - as mentioned in section 2.2. Therefore, we are of the opinion that the decision to narrow the scope was justified to fulfill the practical objectives of the study. Trawler lengths of 12-15m and 24-40m were excluded as their data regarding species composition and amounts are close to the segments included in the study, which already encompass fisheries with both demersal and pelagic target species.

Assessing fuel consumption in fisheries LCA is a common challenge, as national statistics often report it for entire fleet segments based on gear, length, or year. The disaggregation method used to determine relative fuel consumption among different fisheries is a limiting factor in achieving better impact assessment results. The disaggregation method relies on fishery catch compositions from Thrane (2004), which is most likely outdated and does not account for recent changes in fleet structure and practices. Additionally, assuming a fixed composition for

498 each fishery oversimplifies the variability of catches, leading to a quantitatively different composition compared to the baseline when allocating landed fish mass between fisheries.

500 These limitations do not constitute an issue in terms of reproducibility of the research but reduce the accuracy of the results and should be considered when comparing results of this study with carbon footprint estimates from other sources. We stress that, despite being old, data from Thrane (2004) are the only published data regarding composition of Danish fisheries.

504 **5. CONCLUSION**

505 In this study, different modelling approaches and data were considered and applied for the life cycle assessment of Danish fisheries and the uncertainties in the results obtained were discussed in depth. As shown in this study, LCA results are highly model dependent, which means that the influence of modelling choices on the results is key to highlight when different alternative products are compared and when the ranking of these alternatives changes with the modelling assumptions. An uncertainty analysis is always recommended to nuance the communication of results, as well as a precautionary approach when presenting side by side results from different LCA studies– that due to the high number and diversity of modelling choices made are in most cases not directly comparable.

514 For LCA practitioners in the fishery context and beyond, a takeaway from this study is to increase focus on transparency around the implications of modelling choices, in particular when making use of results and in their communication.

517 Since the attributional approach is based on consensus the decision of using one or the other partitioning method is difficult to justify using an objective scientific argument, nor can it be validated. We believe that the approach weakens the systemic understanding of the fisheries context, as it aims to simplify the system under analysis by removing some of its parts and creating virtual monofunctional processes that in some cases are unrealistic, like assuming non-

mixed fisheries where they are mixed. It is in general unclear how scientific improvements can be carried out in an attributional context, besides finding better ways to reach consensus, and it is thus difficult to provide here a recommendation for further research in this direction. On the consequential approach, while it is in principle better suited to model reality and cause-effect relationships in a systemic perspective, the uncertainties for the case of commercial fisheries are large. This is because it relies on assumptions that are oversimplified and need to be better scientifically grounded. Future research should focus on improving our understanding of how constraints in the supply in the fisheries sector affect the assessment of life-cycle related emissions for fish products. This includes identifying sound approaches to measure and anticipate the shift in demand from fish to other food products, which are needed to model both substitution effects and marginals supply within a consequential framework. An improved model of this kind could also help to better comply with the purposes of LCA of decision making and consumers' choice and provide more reliable results from this perspective.

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SUPPORTING INFORMATION

Supporting Information SI 1: This supporting information provides a description and sources of the fuel disaggregation method for the fuel consumption data (1.1); a detailed description of the LCA models used, with technology and intervention matrices (1.2); a description and results of a sensitivity analysis performed to test alternative substitution choices (1.3).

Supporting Information SI 2: This supporting information contains the excel tables with raw data used and calculations performed to obtain the presented results. Furthermore, the R code used to perform the statistical analysis and plot the figures is included.

Figure Legends

Figure 1. Sum of carbon footprint results obtained for each species according to two modelling approaches, consequential and attributional, on the left, and for different vessel lengths on the right.

(Page 19)

Figure 2. full set of results divided in subplots according to vessel length, species, year and modelling methods. The columns of Alternative Route, Constrained and No alternative route belong to the consequential approach while Revenue-based allocation and Mass allocation belong to the attributional approach. The colors indicate which product substitution is performed within the fishery. Note that in the alternative route scenario substitution is applied only to co-products.

(Page 21)

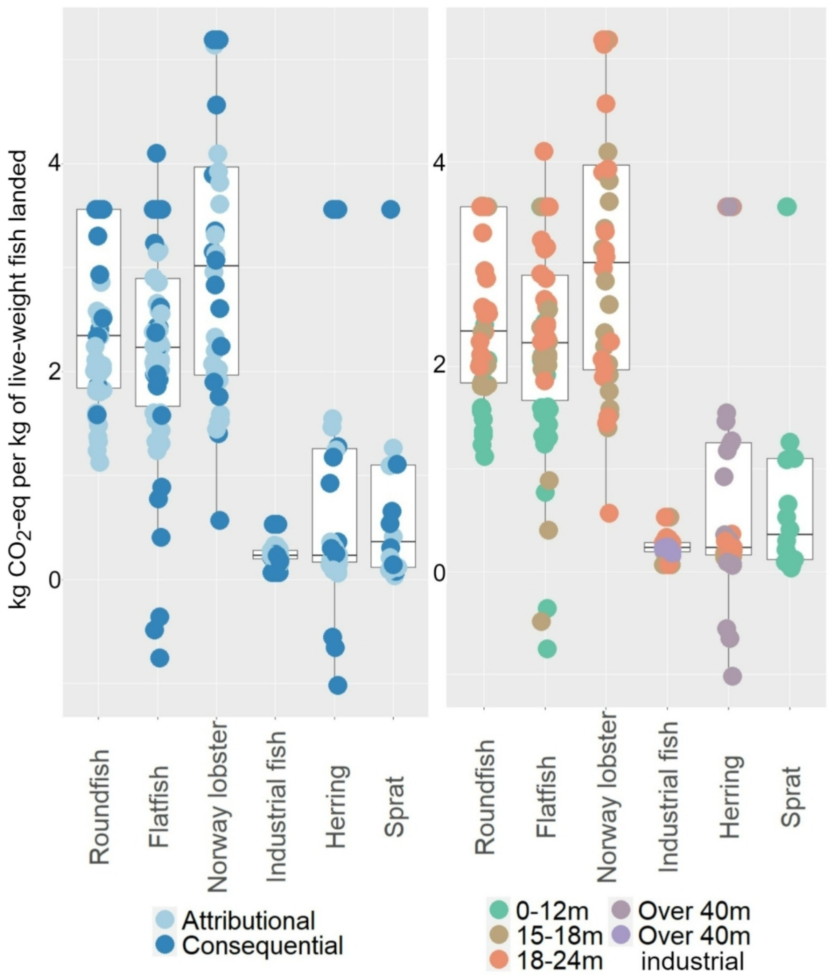
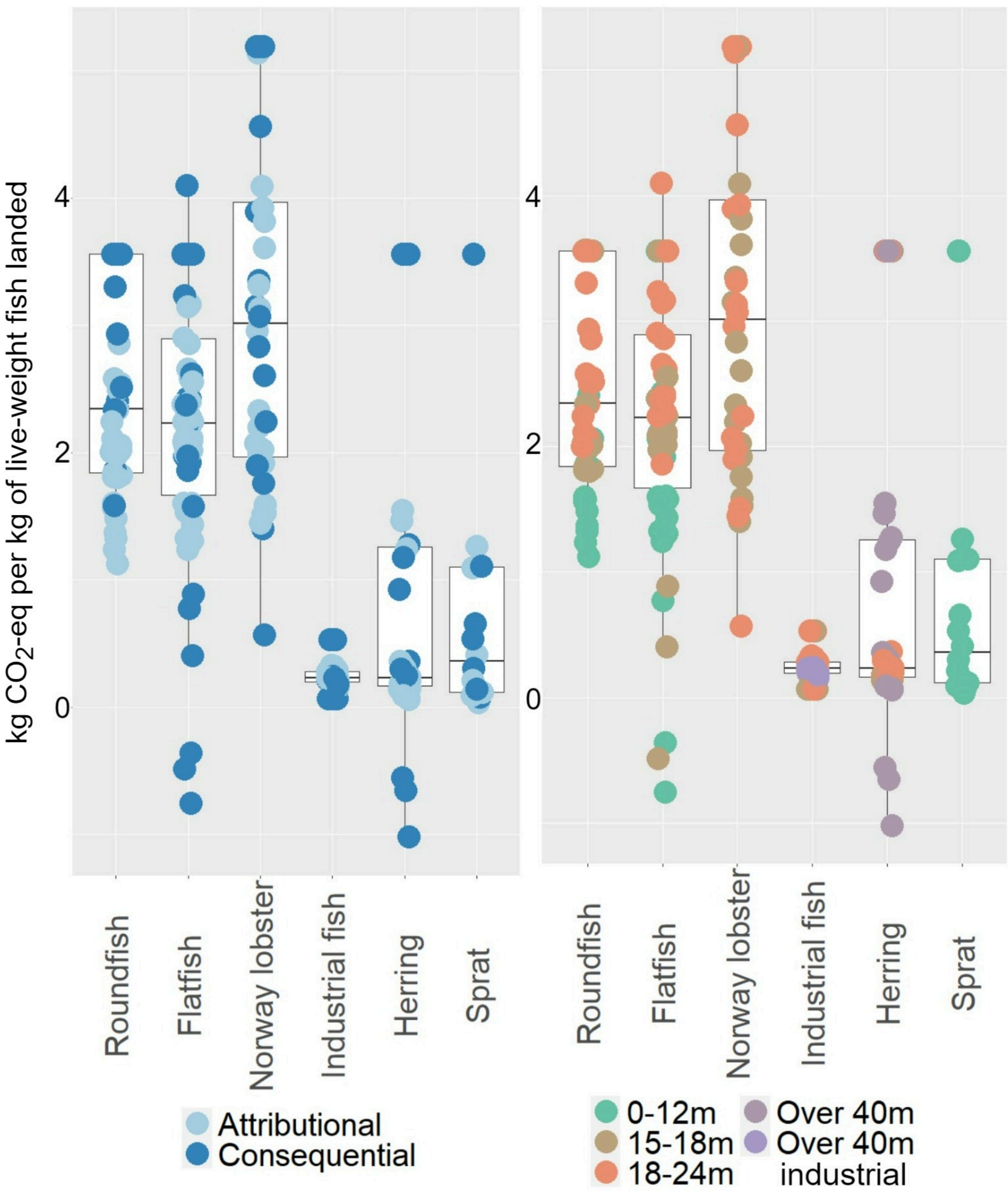


Figure 1. Sum of carbon footprint results obtained for each species according to two modelling approaches, consequential and attributional, on the left, and for different vessel lengths on the right.

601x642mm (72 x 72 DPI)


kg CO2-eq per kg of live-weight fish landed
4
2
0
4
2
0
Roundfish
Flatfish
Norway lobster
Industrial fish
Herring
Sprat
Roundfish
Flatfish
Norway lobster
Industrial fish
Herring
Sprat
Attributional
Consequential
0-12m
15-18m
18-24m
Over 40m
Over 40m industrial

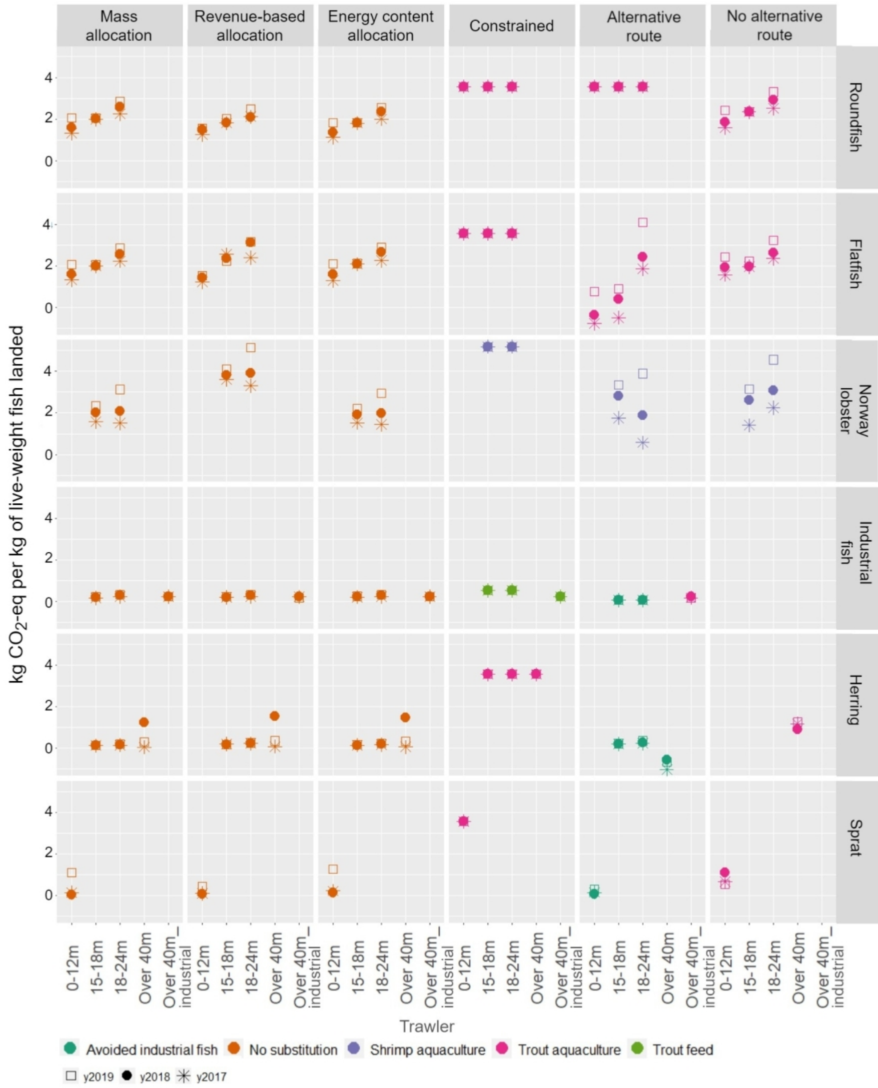
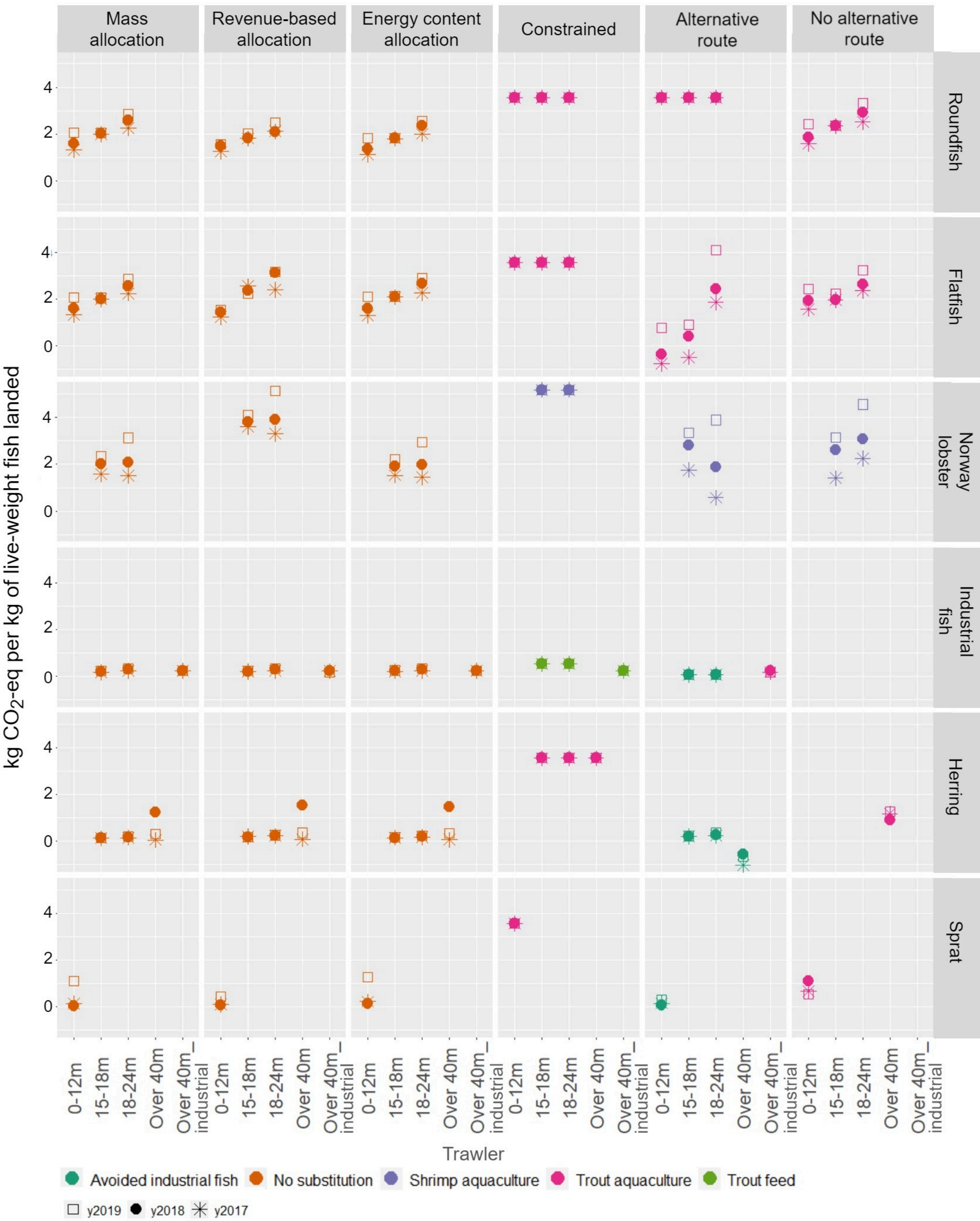


Figure 2. full set of results divided in subplots according to vessel length, species, year and modelling methods. The columns of Alternative Route, Constrained and No alternative route belong to the consequential approach while Revenue-based allocation and Mass allocation belong to the attributional approach. The colors indicate which product substitution is performed within the fishery. Note that in the alternative route scenario substitution is applied only to co-products.

599x740mm (72 x 72 DPI)


Mass allocation
Revenue-based allocation
Energy content allocation
Constrained
Alternative route
No alternative route
Roundfish
Flatfish
Norway lobster
Industrial fish
Herring
Sprat
kg CO2-eq per kg of live-weight fish landed
0-12m
15-18m
18-24m
Over 40m
Over 40m_industrial
Trawler
Avoided industrial fish
No substitution
Shrimp aquaculture
Trout aquaculture
Trout feed
y2019
y2018
y2017