LCA Methodology

Co-Product Allocation in Life Cycle Assessments of Seafood Production Systems: Review of Problems and Strategies

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Abstract

Background, Aim and Scope. As Life Cycle Assessment is being increasingly applied to study fisheries and aquaculture systems, the LCA methodology must be adapted to address the unique aspects of these systems. The focus of this methodological paper is the specific allocation problems faced in studying seafood production systems and how they have been addressed to date.

Main Features. The paper begins with a literature review of existing LCA research of fishing and aquaculture systems with a specific focus on 1) identifying the key allocation problems; 2) describing the choice of allocation procedures; and 3) providing insight on the rationale for those choices where available. The allocation procedures are then discussed in the context of ISO recommendations and other published guidance on allocation, followed by a discussion of the key lessons to be learned from the reviewed studies and recommendations for future LCAs of seafood production systems.

Literature Review. The literature review suggests that allocation problems are most likely to arise when dealing with: landed by-catch within the context of capture fisheries, the use of co-product feed ingredients in aquaculture feeds, multiple outputs from fish farms, and the generation of by-products when seafood is processed. System expansion and allocation according to physical causality were not applied in most cases, while economic allocation was the most widely used approach. It was also observed that the level of detail and justification provided for allocation decisions in most published reports was inconsistent and incomplete.

Discussion. The results of this literature review are consistent with other reviews of allocation in LCA in that allocation according to economic value was found to be the most frequently applied approach. The application of economic allocation when system expansion is not feasible is consistent with ISO guidance. However, economic allocation is not the most appropriate method in seafood production LCAs because it does not reflect the biophysical flows of material and energy between the inputs and outputs of the production system.

Conclusions, Recommendations and Perspectives. More effort needs to be invested in developing allocation procedures appropriate to seafood production systems. Allocation based on gross energy content is proposed as one potential alternative means of allocating environmental burdens in some instances in seafood production LCAs. A standard set of requirements for how to describe and justify allocation decisions in published reports is needed to make these studies more robust and transparent.

Keywords: Allocation; aquaculture; fisheries; gross energy content; LCA; seafood; system expansion

Introduction

Life Cycle Assessment (LCA) of seafood production systems is a growing field of research aimed at improving the efficiency and environmental performance of fisheries and aquaculture systems and providing consumers with better information on how seafood products are produced. While LCA has traditionally been applied to the study of manufactured products, in recent years it has been increasingly applied to quantify the environmental impacts of a range of food production systems. As the methodology is adapted to the study of seafood production, common methodological problems such as co-product allocation must be examined in the context of these newly studied systems to ensure that existing strategies can address their unique aspects.

The choice of allocation procedure has proven to be one of the most controversial methodological issues in LCA, largely because it can significantly influence the results of a study [1,2]. While considerable research has been published on the topic of co-product allocation in LCA, the specific allocation problems faced in LCAs of seafood production have not been formally addressed.

This paper provides a literature review of several existing LCAs of fishing and aquaculture systems with particular focus on 1) identifying the key allocation problems; 2) describing the choice of allocation procedures; and 3) providing insight on the rationale for those choices where available. This literature review is followed by a discussion of these allocation decisions in the context of existing guidance for allocation from the International Organization for Standardization (ISO) and other published literature. The paper concludes with a description of allocation based on gross energy content as an alternative to economic allocation in seafood production systems and a discussion of the need for improvements in the description and justification of co-product allocation decisions in published reports.

1 Co-Product Allocation in LCA

Many production systems are multifunctional in that they produce more than one product. In addition, many raw material inputs to production systems are often intermediate or discarded products from other processes. As a result, a system may provide more functions than the one investigated in a LCA [3]. As a result, the material and energy flows and associated environmental burdens must be allocated to each of its co-products in order to accurately reflect their individual contributions to the environmental impact of the system under study.

The International Organization for Standardization (ISO) has developed a stepwise process for dealing with co-product allocation in the 14044 standard for LCA [4]. According to this standard, the life cycle inventory is based on material balances between the inputs and outputs of the studied system and allocation procedures should reflect these fundamental input-output relationships and characteristics to the extent possible. The following are the three steps outlined in ISO 14044 for dealing with co-product allocation:

(1) Wherever possible, allocation of the environmental burdens associated with the studied system should be avoided, by dividing the multifunction process into subprocesses and collecting the data related to these subprocesses, or by expanding the product system to include the additional functions related to the co-products.
(2) Where allocation cannot be avoided, the environmental burdens of the system should be allocated according to an underlying physical relationship that reflects the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.
(3) Where such a physical relationship cannot be established, the allocation should reflect other relationships between the inputs and outputs of the system, such as economic value.

The ISO standard also states that when several alternative allocation procedures seem applicable a sensitivity analysis should be conducted to illustrate the impact of the different allocation procedures on the results of the study, and the allocation procedure used for each unit process should be documented and justified.

2 Literature Review: Co-Product Allocation in LCAs of Seafood Production Systems

This section provides a review of the four key allocation problems faced in LCAs of fishery and aquaculture systems carried out to date. Information is provided on the nature of the allocation problems, the allocation procedure chosen by the researchers in each study, and an explanation of the rationale where available. The scope of the review does not include post-processing stages such as retail or consumption as these allocation problems are not unique to seafood production systems and are frequently excluded from seafood LCAs.

2.1 Fishery stage

Co-product allocation is often necessary in LCAs of capture fisheries because of the existence of by-catch (those organisms inadvertently captured while fishing for more valuable or legally permitted species). Levels of by-catch vary widely between fisheries depending on the species targeted, the gear type used, the location or season of fishing, etc. While by-catch is often discarded at sea, some may be landed along with the targeted species. In instances where by-catch is landed, a fraction of the direct and indirect inputs to the fishing enterprise, along with the resulting environmental burdens, need to be allocated between the target species and the landed by-catch. Depending on the amount of by-catch landed, its composition, and ultimately its value relative to the targeted landings, this allocation decision can have a significant impact on the results of the study. A review of existing studies indicates that at least three different allocation procedures have been used to address allocation in the fishery stage.

In an LCA of Swedish frozen cod fillets [5], the allocation of environmental burdens between the target species Atlantic cod (*Gadus morhua*) and the associated landed by-catch was apportioned according to their relative economic value. Using average 1999 ex-vessel prices for all species landed, cod was found to represent approximately 99% of the value of the total catch. Therefore 99% of the environmental burdens associated with fishing were allocated to cod. The rationale provided for applying economic allocation was that 1) system expansion was not possible because there are no fisheries where only the by-catch species are caught; and 2) due to low levels of landed by-catch in the Baltic cod fishery (representing <1.5% by weight and <1.0% by value), allocation by economic value or mass would have provided nearly the same result. This observation is supported by earlier research on this fishery [6]. It was also argued that economic allocation is more socially relevant in this type of study because the economic value of the cod is the driving force for the fishery.

According to the catch statistics in a recent LCA of the Norway lobster fishery in Sweden [7], Norway lobsters (*Nephrops norvegicus*) captured in the trawl fishery represented 59% of the economic value of the catch, 26.8% of the mass, and 27.6% of the edible energy content. The allocation of environmental burdens between the target species (Norway lobster) and landed by-catch (cod, plaice, other fish and whiting) was done according to their economic value. According to the author, avoiding allocation by system expansion was not feasible because there are no fisheries that land each of the by-catch species separately. It was also argued that system expansion would make the results less transparent because a number of assumptions would need to be made about what type of production is displaced by the by-catch. According to the author, economic allocation has been shown to be preferable over other allocation methods (e.g. mass) in mixed fisheries where the landed species have great differences in economic value [6]. It was also argued that allocating by mass or energy content would have led to less accurate results because this would have attributed a lower share of the environmental burden to the Norway lobsters even though the value of this species is the primary reason for the existence of the fishery.

In an LCA of Danish flatfish [8], the environmental burdens associated with capturing flatfish (various spp.) were determined by using system expansion to avoid allocation between the target species and landed by-catch. The Danish flatfish fishery has high levels of landed by-catch which generally is comprised of up to eight different species, each of which is targeted in one or more other fisheries. Data were collected on these eight fisheries and the system expansion was carried out under the assumption that the outputs of all fisheries in the study are restricted by national species-specific quotas. Within this system, landed by-catch in the flatfish fishery would indirectly affect the fisheries targeting the landed by-catch species as their quotas would be reduced proportionally to meet the overall quota limits for the Danish fleet. The use of system expansion to avoid allocation in the fishery is best illustrated in an example from Thrane's work on the fuel inputs to the Danish fishery [9]:

Vessel A, which targets cod, consumes 50 L of diesel to capture 100 kg of cod. Vessel B, which targets flatfish, consumes 60 L of diesel to capture 20 kg. The amount of fuel allocated to the capture of flatfish should be the fuel consumption for the flatfish vessel (B) minus the fuel consumption needed to capture 20 kg of codfish, which is 10 L based on the data from the vessel targeting cod (A). Therefore, 50 L of diesel would be allocated to the capture of 40 kg of flatfish, or 1.25 L/kg.

In the Danish flatfish study the system expansion was far more complex than this illustration because it included eight other fisheries, each with their own respective levels and mix of landed by-catch. However, Thrane argued that this was simply a mathematical problem and applied linear algebra to calculate the allocation of environmental burdens (see [8] for details of calculations).

A study of the environmental impacts of the Icelandic cod fishery reported significant levels of by-catch [10]. In this case, however, the environmental burdens associated with the fishing effort were allocated in proportion to the mass of the landings. As cod represented 44% of the mass and 48% of the economic value of the landed fish, the authors argued that economic or mass allocation would have given a similar final result and that mass allocation was selected because mass is less time-dependent. In other words, the results better reflect reality over longer time periods and changing economic conditions.

In a study of shrimp aquaculture in Thailand, a fishery-related allocation problem was faced in the broodstock collection stage [11]. Broodstock for shrimp farming in Thailand is captured by trawlers that simultaneously fish for other species, including those used to make fish meal for shrimp feed. These trawlers use the same gear for capturing fish and for capturing broodstock by making alternate trawls for each catch. The broodstock is then transported by speedboat from the trawling area to a designated transfer point, and then to the hatchery. In a typical month a trawler will land 5000 kg of target fish, 15000 kg of by-catch, and 400 individual shrimp for broodstock. According to the author, system expansion and allocation according to physical causality were not applicable and therefore in accordance with the ISO guidelines allocation was used based on the economic value of the three products (**Table 1**). As a result, approximately 95% of the environmental burdens associated with the fishing effort were allocated to the shrimp broodstock.

It is interesting to note that in this case the author calculated the economic allocation according to the relative prices of the target species and landed by-catch, and not the mass-adjusted economic values of the catch. Had the values been mass adjusted, approximately 57% of the environmental burdens would have been allocated to the shrimp broodstock. This is a potential source of error when applying economic allocation. Mass-adjusted values have been provided in Table 1 for comparison.

In an LCA of Norwegian wild caught cod and farmed Atlantic salmon (*Salmo salar*), mass allocation was used in the cod fishing stage to allocate between the cod landed and the landed by-catch, which consisted mostly of other groundfish species [12].

2.2 Processing stage

The processing of fish into marketable products results in varying levels of waste and by-products depending on the species being processed and the end product form. The by-products of fish processing are often used as protein sources in other production systems and frequently represent a significant portion of the mass flow in processing. As a result, it is generally necessary to allocate the environmental burdens of fish processing between the primary product and one or more by-products.

In the LCA of frozen cod fillets [5] the processing stage yielded cod fillets and two by-products: fish mince and 'cod parts' (the fish racks including bone, skin, head and offal) (**Table 2**). Economic allocation was applied because according to the author the by-products in the processing stage represented over 50% of the mass flow. It was reasoned that mass allocation would have greatly reduced the share of environmental burdens attributed to the cod fillets, the functional unit of the analysis. Applying economic allocation attributed 75% of the environmental burdens to the cod fillets. According to the authors this was a more appropriate allocation of environmental burdens considering that cod fillets are the primary product and economic motivation for the fishery concerned.

Table 2: Co-products of cod processing in Swedish cod fishery (from [5], p 40)

Product	Relative Mass	Relative Value	End Use
Fish mince	14%	23%	Fish finger industry
Cod fillet	38%	75%	Consumer
'Cod parts' (skin, bones, etc)	48%	2%	Pet food industry

Table 1: Allocation of trawling impacts in Thai shrimp broodstock fishing (modified from [12], p 106)

Product	Mass Landed	Market Price	Unit Price Based Economic Allocation	Mass- Weighted Economic Allocation
Shrimp broodstock	400 individuals	1500–2500 baht each	94.6%	57.0%
Target fish	5000 kg	20–200 baht/kg	5.2%	39.2%
By-catch	15000 kg	2–5 baht/kg	0.2%	3.8%

In the LCA of the Danish flatfish fishery [8] the processing stage produced fish fillets, fish mince and fish offal (bone, skin and head). Allocation between the fillets and the by-products was avoided by using system expansion. The system expansion was based on the assumption that fish mince and fish offal can be used as protein sources in other production systems and therefore would offset the environmental burdens associated with producing these alternative protein sources. It was assumed that fish mince is used to produce fish balls and other similar products and that these protein sources were reasonable substitutes for pork. Similarly it was argued that fish waste from flatfish is typically processed into mink fodder where it serves as a protein supplement and is therefore a reasonable substitute for soy protein. Based on these assumptions the system was expanded to include the production of these alternate protein sources (pork, soy protein), and the environmental burdens associated with these systems were subtracted from the flatfish processing system, with the remaining environmental burdens allocated to the processed flatfish fillets.

In the LCA of Icelandic cod [10], the cod trawlers processed the fish on the boat, generating significant amounts of waste and by-products in the process (**Table 3**). Approximately 28% of the cod was returned to the sea as waste, and 30.5% was retained onboard as by-products that are used for fish mince, dry fish heads, etc. In their report, these authors provide no indication of how they allocated environmental impacts between the cod fillets and the retained by-products. Consequently, it is assumed that 100% of the impact of processing was allocated to the cod fillets – effectively treating all non-fillet portions of the cod as discards.

In the LCA of Thai shrimp farming [11] the processing of shrimp into marketable products involved trimming and then freezing the shrimp into blocks. For every 3 kg of farmed shrimp processed there was approximately 0.9 kg of shrimp heads and 0.3 kg of defective shrimp produced, as well as flesh that is dispersed in the wastewater during the washing stage. While shrimp heads are sometimes sold to animal feed factories, they are more often than not disposed of. Considering this, and the fact that no inventory data were available for the animal feed factories, the author treated the shrimp by-products as waste and allocated 100% of the environmental burdens associated with shrimp processing to the frozen shrimp product.

In an LCA of canned Tuna processing [13], the authors considered using economic allocation to allocate between the main product (canned Tuna) and the by-products. However, it was decided to allocate 100% of the environmental burdens to the canned Tuna because the by-products accounted for only 0.5% of the total economic value.

Table 3: Co-products of cod processing in Icelandic cod fishery (from [11], p 15)

Product	Relative Mass	End Use
Cod fillet	41.5%	Sold to consumer
Cod head	28%	Unspecified
Skin	2.5%	Unspecified
Offal	16%	Returned to sea
Bone	12%	Returned to sea

2.3 Feed production stage

The concentrated feeds used in modern aquaculture generally contain numerous ingredients which are by-products of other processes. For example, a generic salmon feed may contain feather, meat and blood meals from poultry production, corn gluten meal from the wet-milling of corn, and soybean meal from soy production [14]. When quantifying the environmental impacts of an aquaculture feed, the burdens associated with these by-products must be determined by allocating the impacts of the upstream production system (e.g. poultry production) between the main product (marketable chicken pieces) and the resulting by-products (e.g. feather meal, etc.). This can be both challenging and complex since data must be obtained for the upstream production processes from which the co-products originated and there may be dozens of such by-products used in feeds.

The environmental impacts associated with salmonid feeds were examined in an LCA study of four hypothetical feeds that varied primarily in the quantity and source of the fish meal incorporated [15]. The authors of this study applied economic allocation for all processes in the feed production system that yielded by- and co-products. One of the key objectives of this study was to quantify the changes in environmental impact when feed components were varied from high fish meal content toward a feed containing mostly plant-derived ingredients. One of the four hypothetical feeds, called HF (high fish), was comprised primarily of fish meal coming from the dedicated Norwegian and Peruvian reduction fisheries. An alternative to this feed was a high fish by-products feed (HFBP) in which the Norwegian-sourced fish meal was replaced with fish meal derived from by-products of the food-grade fish processing industry in France. In order to quantify the change in environmental impacts resulting from switching to the by-products fish meal, there was a need to determine what proportion of the environmental burdens associated with the food-grade fishery should be allocated to the processing by-products. In this case the economic values of the primary product and various by-products were used as the basis for allocation. Specific values for this allocation are not provided in the report; however it is assumed that the by-products have a very low economic value relative to the main products of the food-grade fishery. Consequently a very small percentage of the environmental burdens associated with acquiring and processing the fish were allocated to the by-products. This assumption is reflected in the results of the study where the HFBP feed was found to have a lower environmental impact than the HF feed in four out of the five impact categories considered. According to the authors, this was a result of using economic allocation which resulted in a small share of the burdens being apportioned to the relatively inexpensive by-products.

A study of farmed rainbow trout (*Oncorhynchus mykiss*) production in France used data on feed production from this study [15] and economic allocation was also applied for all processes yielding by- and co- products [16].

In the LCA of Thai shrimp, the feed used on the farms was comprised of several by-products from other processes [11]. Economic allocation was used to apportion the environmen-

Table 4: Allocation in rice production (from [12], p 115)

Product	Relative Mass	Market Price	Mass-Weighted Economic Allocation
Edible rice	92%	18 baht/kg	98.0%
Rice bran	3%	8 baht/kg	1.4%
Rice husk	5%	2 baht/kg	0.6%

tal burdens associated with the upstream processes in the feed production stage to their various products and by-products (**Table 4**). For example one of the ingredients was rice husk, a by-product of rice production. Rice production produces 92% edible rice, 5% rice husk and 3% rice bran by weight. It was argued that economic allocation was the most appropriate procedure for dealing with this allocation problem since the co-products of rice production cannot be varied independently. Based on the relative mass-corrected values of each of the three co-products, approximately 0.6% of the environmental burdens associated with rice production were allocated to the rice husk.

2.4 On-farm stage in aquaculture systems

Generally the on-farm stage in aquaculture systems produces only one product, the harvested fish species, along with various waste products such as uneaten food, mortalities, fish feces and liquid waste. However, depending on the form of aquaculture, there may be more than one species or product being produced on a farm. For example, in the LCA of shrimp farming in Thailand, a comparison of the environmental impacts of five different types of shrimp farms featured a farm that produced 1107 kg of tiger prawn, 42 kg of freshwater prawn and 63 kg of non-target shrimp from the same culture environment. As a result, an allocation decision was required to determine the environmental burdens associated with producing these various species on the same farm. The author argued that system expansion and allocation according to a causal relationship were not feasible because the products of the shrimp farm could not be varied independently, and thus economic allocation was applied (**Table 5**). Based on the economic value of each of the three species produced, approximately 59% of the environmental burdens associated with the overall production at this farm were allocated to the tiger prawn product.

It is interesting to note that, similar to the broodstock fishing stage, the author calculated the economic allocation based only on the relative unit prices of the harvested species and not the mass-adjusted economic values of the harvest. Had the values been mass adjusted, approximately 97% of the environmental burdens would have been allocated to the tiger prawn. This is a potential source of error when applying economic allocation. Mass-adjusted values have been provided in Table 5 for comparison.

3 Discussion

3.1 Overview of key results from literature review

The preceding literature review reveals that allocation problems in LCAs of seafood production systems are most likely to arise when dealing with 1) landed by-catch within the context of capture fisheries; 2) the use of co-product feed ingredients in aquaculture feeds; 3) multiple outputs from fish farms, and 4) the generation of by-products when seafood is processed. Researchers in the reviewed studies have handled these allocation problems by generally following the hierarchy of procedures outlined in ISO 14044. However, it is apparent from the review that the first two steps of the ISO hierarchy have been difficult to apply. With the exception of the Danish flatfish LCA, researchers generally argued that neither sub-dividing the systems studied nor allocation according to a causal physical relationship were possible. As a result, researchers have generally applied step 3 of the ISO guidelines on allocation which states that when a causal physical relationship cannot be defined, allocation according to other relationships should be conducted. In past LCAs these other relationships have typically been non-causal physical relationships such as mass or energy content, or the economic value of the co-products, which was the most frequently applied approach in the reviewed studies. The literature review also reveals a general lack of consistency in the level of detail and discussion provided about specific allocation problems in published reports. This is problematic and will be addressed in more detail in section 3.3.

The results of this literature review are consistent with other papers in which allocation problems in LCA have been reviewed. The first option in the ISO guideline, avoiding allocation by subdividing the system, has been shown to rarely be possible in practice since a multifunction process is not likely to consist of physically separate sub-processes [2,17]. While avoiding allocation by system expansion is generally recommended as the next best approach [1,3,4,18–20], the predominant practice in LCA has been to apply step 3 of the ISO guideline and allocate according to economic value or according to physical properties such as mass, energy or volume [2]. Similarly, economic or mass-based allocation has been used most frequently in agricultural LCAs [18]. While economic allocation has generally been defended as a reasonable approach [21], several researchers have argued that allocation according to physical properties such as mass or energy is arbitrary and unjustified [17,21]. However, despite these criticisms this type of allocation has been prevalent in LCAs to date. Allocation according to a causal physical relationship has rarely been applied in LCAs of food production systems to date. One exception is an LCA of Swedish milk and beef production where allocation according to a causal relationship between the dairy cow's feed mix and its production of milk, calves and meat was ex-

Table 5: Allocation for the 'Going to be Organic' farm in Thai shrimp farming (modified from [12], p 123)

Product	Mass Harvested	Market Price	Unit Price-Based Economic Allocation	Mass-Weighted Economic Allocation
Tiger prawn	1107 kg	170 baht/kg	58.6%	97.0%
Freshwater prawn	42 kg	80 baht/kg	27.6%	1.7%
Non-target shrimp	63 kg	40 baht/kg	13.8%	1.3%

plored as part of a sensitivity analysis [20]. However, the authors of this study determined that system expansion was the only allocation method that would provide appropriate information. While previous research has shown that allocation according to a causal physical relationship should be possible when the co-products of a system are physically independent of one another [2], this type of allocation is not possible in seafood production LCAs because the co-products of the systems under study cannot be varied independently. For example, in the processing of whole fish, a fish processor cannot choose to produce more fish bones or offal. The quantity of these by-products is limited by the size and species of the fish, the processing technology, and the end product. Similarly, in capture fisheries, the amount of landed by-catch and its species composition cannot be varied independently but instead will vary according to the gear type, location fished, time of year, and the species targeted.

In general, researchers in the reviewed seafood studies argued that avoiding allocation by system expansion was not feasible due to a lack of alternative production systems or a lack of available data describing an alternative production system. In the LCAs of Swedish cod and Norway lobster fisheries it was argued that system expansion was not feasible because there were no alternative fisheries that captured only the by-catch of the studied fisheries. The author of the Thai shrimp LCA maintained that system expansion and allocation based on causal relationships were not feasible because the products and by-products could not be varied independently. While Thrane showed that system expansion may be possible in the fishery and fish processing stages, the results of this literature review suggest that the system expansion will not be widely applied in subsequent seafood LCAs, and it appears that economic allocation will continue to be the favoured allocation method. This is further supported by a more recent article on the Danish flatfish study where Thrane noted that although system expansion may provide the truest picture of the relative impacts of the fisheries, economic allocation may also be appropriate in many cases since fishermen will exert a greater fishing effort when more valuable species are available [22].

The frequent use of economic allocation in seafood production LCAs may be problematic on a number of counts. While the choice to apply economic allocation when system expansion is not possible is consistent with ISO recommendations and other published guidance, it is not necessarily the best approach. The ISO guidelines state that allocation procedures should as much as possible reflect the material balances between the inputs and outputs of the studied system [4]. As such, a good allocation procedure should consistently reflect the biophysical flows of material and energy between the inputs and outputs of a production system. However, the economic values of co-product streams may often not provide an accurate reflection of the flows. The use of economic allocation to proportion burdens between co-product streams in feed production for aquaculture provides an excellent illustration. One of the primary ingredients of the conventional aquaculture feed described in the LCA of salmonid feeds [15] is fish meal derived from dedicated reduction fisheries in Norway and Peru. A proposed alternative is the production of fish meal from the by-products of food-grade fish processing in France. An allocation problem arises here because the environmental impacts associated with the food-grade fishery must be allocated between the main product (fish fillets) and the by-products that will be used to produce fish meal. Since the authors of this study applied economic allocation, and the by-products in this case have a very low economic value, the feed containing fish meal derived from these by-products had a significantly lower environmental impact in four of the five impact categories considered. However, if the demand for these by-products were to increase in the future due to their increased use in fish meal production or other food production processes, their economic value would also likely increase. As a result, the reported environmental impacts of deriving fish meal from these by-products would be higher in any subsequent study that applied economic allocation. This is problematic because in reality the material and energy flows associated with the production and use of these by-products will remain constant. However, due to the change of the perceived value of the by-products the results of the LCA would be different. An appropriate allocation method should be consistent over changing economic and geographic conditions. However, the economic value of a product can be highly variable over time and location. This inherent weakness in using economic allocation was previously identified in the LCA of Icelandic cod [10], where mass allocation was selected over economic allocation in the fishery stage because total allowable catch limits for cod are declining globally and therefore the price fluctuates considerably according to the supply of fish.

Despite these weaknesses, several researchers have argued that economic allocation should be selected in order to ensure that the product under study is apportioned the majority of the environmental impacts because the value of the product reflects the incentive for production. This approach may be appealing from a conservation perspective, however, from a purely scientific perspective, there is no value in ensuring that the product under study is allocated a majority of the burdens. The allocation procedure selected should be that which best reflects the biophysical flows of material and energy (and the associated impacts) between the inputs and outputs of the production process regardless of whether or not the share of impacts apportioned to the product under study is thought to be appropriate.

3.2 Allocating according to gross energy content

It is apparent from this review that researchers in seafood LCAs have not found it feasible to avoid allocation and have therefore chosen to allocate environmental burdens according to economic value in most cases. Greater effort needs to be invested in the development of new approaches to allocation that are both more relevant to seafood products and representative of biophysical reality. Given that the co-products of seafood production systems cannot be varied independently, new approaches to allocation in these systems will need to be based on 'other relationships' as described in Step 3 of the ISO guidelines. Allocation according to physical properties such as energy content has been traditionally downplayed in the published literature as an arbitrary method that does not generally reflect the relationship between the inputs and outputs of a studied system. However, in the context of food production systems, gross chemical energy content represents a common physical property of food co-products both within and between production systems and therefore may provide a consistent unbiased allocation method that is more relevant in some instances for seafood production systems. While the gross chemical energy content of food co-products does not represent a causal physical relationship between the inputs and outputs of the system, it does represent a physical relationship that is much more closely linked with the biophysical flows of material and energy in food production systems than the economic value of the co-products.

Co-product allocation based on gross chemical energy is appealing on a number of fronts. First, although biotic resources have many potential uses, such as nutrition, energy generation, construction materials, etc., gross energy provides a value-neutral representation of resource flows. The gross energy content can also be said to reflect the function of the products at hand; to feed animals and, ultimately, to feed people. In ecological terms, it effectively captures how energy flows across trophic levels because the gross chemical energy content of a food co-product represents its relative worth in the competition for food resources. Naturally, the metabolic efficiency of different animals will vary with species and foodstuff. For example, fish catabolize protein more efficiently than terrestrial farm animals, and also have much lower maintenance energy requirements. At the same time, certain animals are able to digest specific kinds of feeds more efficiently than others. In light of these differences, gross chemical energy represents a common denominator for biologically available potential energy in food. Digestible or metabolizable energy for specific species can then serve as secondary criteria in determining the optimal use of food resources.

Perhaps most attractive in using gross chemical energy to allocate environmental burdens between co-products is that it bridges biophysical and economic considerations. As described previously, various LCA researchers have defended the use of economic allocation based on the social preferences driving industrial production systems. For example, Ziegler et al. [5] chose economic allocation in the processing stage for fishery-caught cod because mass-based allocation would have attributed a significant share of the environmental burdens to trimmings which were recycled in the pet-food industry. It was argued that the fishery existed to produce cod fillets, not pet food, and that the fillets should therefore be apportioned a greater responsibility for impacts. However, it could be argued that the very purpose of using tools such as Life Cycle Assessment is to internalize the environmental costs that economic theory typically treats as externalities. Using gross energy over economic allocation results in a biophysically defensible apportioning of burdens while at the same time reflecting multiple social preferences. If allocation according to gross chemical energy had been applied in the processing stage of this study, less than 50% of the environmental burdens would have been attributed to the cod fillet, in contrast to 75% when economic allocation was applied. While this result may not reflect the motivation for fish processing it does provide a more accurate reflection of the flow of matter and energy in this production system and is therefore a more defensible allocation procedure.

Table 6: Sensitivity analysis for allocation in corn wet-milling

Co-Product	Mass Allocation	Economic Allocation	Energy Allocation
Corn Gluten Meal	6.7%	10.0%	8.9%
Corn Gluten Feed	23.8%	8.0%	12.8%
Corn Starch	61.0%	78.0%	67.3%
Corn Germ Meal	8.5%	4.0%	11.0%

Allocation according to gross chemical energy is also appealing in the aquaculture feed production stage where feed formulators strive to deliver energy-dense feeds that satisfy animal nutritional requirements, maximize efficiency, and minimize costs. For example, corn gluten meal, a co-product of corn wet-milling, is a common ingredient in salmon feeds. Although corn gluten meal comprises a small fraction by mass of corn processing outputs, it is energy-dense compared to some of its co-products (e.g. corn gluten feed), and is thus attractive to feed formulators. Allocating burdens based on the relative gross energy of corn processing co-products simultaneously captures the physical division of feed energy and the criteria by which the co-products are valued. A sensitivity analysis of three allocation procedures for corn wet-milling is presented in **Table 6**.

Using gross energy as the allocation criterion for food co-products might, however, generate different results depending on the production system studied and the functional unit chosen. In salmon aquaculture, for example, because salmon feeds typically contain a high proportion of by-product ingredients, gross energy allocation will result in substantially higher apportioning of burdens to the salmon production system than would economic allocation. inally, using gross energy as the allocation criterion for food co-products is also attractive in that it discourages wastage of biologically valuable materials, regardless of their economic value. For example, at the processing stage in both fisheries and aquaculture, the co-product trimmings will be apportioned a share of the life cycle environmental burdens in relation to their energy content only if they are cycled back into the food production stream (i.e. for use in animal feeds). If the trimmings are disposed of as waste, then the primary product (fillets) will be assigned the full weight of the life cycle burdens. In contrast, due to the low economic value of the trimmings, the weight of burdens borne by the filets would be similar regardless of the fate of the trimmings were economic allocation to be used.

3.3 Reporting of allocation decisions and sensitivity analysis

ISO 14044 states that when several alternative allocation procedures seem applicable, a sensitivity analysis should be conducted to illustrate the impact of different allocation procedures on the results of the study and the allocation procedure used for each unit process should be documented and justified [4]. However, this important directive has not been followed in the majority of LCAs reviewed in this study. While it is assumed that the authors of each of the reviewed studies conducted sensitivity analysis and explored the rationale for their choice of allocation procedure, there was a lack of consistency in how these details were reported. Descriptions of allocation methodology ranged from a single line in a data table [15] to several paragraphs and a table showing sensitivity analysis [9].

Considering the significant impact that allocation methodology can have on the overall results of a life cycle assessment there is a need for a consistent, standardized approach to documenting and reporting allocation decisions in published articles. At a minimum authors should be required to provide a brief description of each allocation problem, a description of the rationale for their choice of allocation procedure (e.g., why economic allocation was chosen over the other options), as well as a data table showing the sensitivity analysis conducted. This will allow readers of published studies to make determinations about the validity of the results, to replicate the study on other systems, and to raise directed questions about the appropriateness of the allocation procedures applied.

4 Conclusions, Recommendations and Perspectives

This review has shown that dealing with co-product allocation is an integral part of carrying out life cycle research of fisheries and aquaculture production systems. Allocation problems will generally arise when dealing with by-catch at the fishery stage, by-products of the processing stage, by-product ingredients in the feed production stage and, in some cases, in the on-farm production stage. Authors of the reviewed studies adhered to the allocation procedures outlined in ISO 14044 but in general argued that they were not able to avoid allocation by subdividing or expanding the system and chose to allocate environmental burdens based on some other relationship between the inputs and outputs, primarily economic value. However, the economic value of co-products is variable over time and location and does not reflect the biophysical flows of material and energy (and the associated environmental impacts) in a production system and therefore may not be the best approach for allocating in LCAs of seafood production systems. Greater effort needs to be invested in developing more relevant allocation procedures. Allocation according to gross chemical energy content has been explored in this paper and, along with other methods, should be explored further in future studies. It is also important to improve the standards for describing and rationalizing allocation decisions within published reports. More detailed descriptions of allocation decisions will make the results of the studies more robust and provide other researchers with greater insight into how a particular allocation problem was handled so that they can question the work or apply the method to their own research. If LCAs are published without providing this information then this will encourage the indiscriminate use of allocation procedures and provide even less incentive for practitioners to review their allocation decisions critically. As LCA is increasingly used to study seafood production systems, the development of more appropriate allocation procedures will improve the ability of researchers to accurately describe and analyze these systems. This process will be greatly enhanced by improvements in the reporting standards for allocation decisions.

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