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# Interactions between aquaculture and fisheries

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ABSTRACT

Aquaculture is increasingly interacting with fisheries from a socio-economic perspective at the level of the global food market. In addition, since 36% of landings from fisheries are used for the production of fishmeal and fish oil, which are essential feed elements for many aquaculture species, another source of interaction is at the level of the aqua feed market. The relevance of the interactions between the two sectors is becoming more evident as the process of transition from fishing to farming has reached a pivotal point, with almost 50% of the fish food supply now coming from aquaculture. The analyses on aquaculture and fisheries interactions often result in diverging views. This paper reviews the main positions in the recent scientific literature, structuring the discussion along the following themes: food market interactions; comparison of resources use by means of Life Cycle Assessment; use of fishmeal and fish oil and aqua feed markets; impacts on small pelagic fish stocks; food security; technical substitution of fishmeal and fish oil with alternative ingredients. The review is not aimed at taking a definitive position in respect of these complex issues but rather at summarising the different scientific contributions and indicating possible areas for further research. Research on fisheries and aquaculture interactions is considered beneficial in terms of policy support especially now that the reform of European Common Fishery Policy is assigning greater relevance to the growth of aquaculture and to its role in terms of socio-economic development for coastal and rural communities. In a more global perspective, the understanding of interactions between aquaculture and fisheries is important to evaluate the respective contributions to food security goals and the implications in terms of environmental sustainability and resource use efficiency.



## 1. Introduction

The latest FAO report on the state of the world fisheries and aquaculture [1] indicates in 2009 a global aquaculture production of 55.1 million tonnes (aquatic plants excluded) and global marine catches of 90 million tonnes. Around 27.3 million tonnes of global marine catches were destined for non-food purpose, of which 20 million tonnes went into reduction to fishmeal and fish oil. Over the last decade, the figures from FAO showed the world aquaculture production continuously growing, while during the same period the amount of captured fish used for fishmeal and fish oil production remained relatively stable (Fig. 1).

The average year to year growth rate for aquaculture production between 1970 and 2009 was 8.3%, compared to 4.9% for poultry, 2.9% for pig, 1.8% for sheep and goats, 1.4% for cattle and 1.2% for fisheries. While the trend in productivity gain for agriculture and livestock production after the "green revolution" is slowing down, aquaculture has still to exploit its full potential to increase productivity through the domestication of new species [2], genetics, genomics and selective breeding [3], and more in general through an intensification of production systems [4]. The expansion of aquaculture in respect to fisheries can be considered as the latest process of animal domestication and transition from "hunting to farming". The figure of almost 50% (45.7%) of global supply of seafood coming in 2009 from aquaculture represents a pivotal point in this transition.

Global forecasts on food security [5,6] indicate that aquaculture will compensate for the stagnating supply of seafood from fisheries and give an important contribution in feeding the growing human population with valuable animal proteins. This represents on one side an opportunity in responding to food security needs and alleviating the pressure on marine resources but, on the other side, raises several sustainability concerns [7].

With the increasing contribution from aquaculture to seafood supply the interactions between fisheries and aquaculture are expected to become even more important and therefore deserve exhaustive investigations from socio-economic and biological perspectives.

A key element that characterises aquaculture in respect of fisheries is the higher degree of control on the production process that is associated to stronger property rights. Anderson [8] pointed out that there is a tendency of fisheries to become closer

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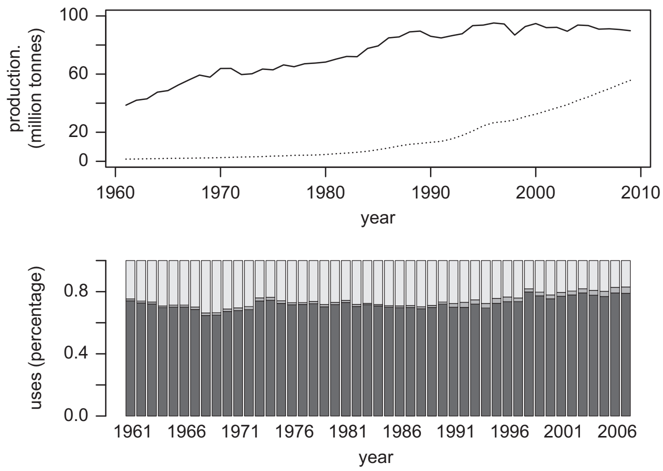


**Fig. 1.** Production from aquaculture and fishery (dotted and solid lines in chart above) and uses for food, other uses and feed (dark grey, medium grey and light grey in chart below) (source: FAO). The transition from fishing to farming has reached a pivotal point with farmed fish now representing almost 50% of total seafood supply. Contrary to pessimistic predictions the expansion of aquaculture has not resulted in higher use of capture fish for fishmeal production.

to aquaculture since fishery management and in particular the adoption of fishing quota are introducing the equivalent of property rights on the common pool resource of fish stocks.

Not only the two sectors are becoming similar but in economic terms they are increasingly interacting at the level of the food market and from the input side through the dependence on fishmeal and fish oil as key ingredients in aqua feed.

At the food market level the substitution between farmed and wild fish is affecting prices and the profitability of the respective industries. These interactions take place at a global scale given the role of international trade, which is particularly relevant in the case of fish products. The fate of local economies in coastal areas relying on fisheries as primary source of food and income is affected not only by shifting patterns of global fisheries [9] and allocation of fishing rights but also by an increasing share of farmed fish in international trade.

Even if markets for fish may not be fully integrated they are at least complementary. Farmed fish may complement the supply outside the fishing season and the marketing and processing after harvest are very similar. Large companies have realised that there are significant benefits in operating in both fishing and aquaculture sectors. These synergies have led to horizontal integration with fishing companies starting to merge with aquaculture enterprises and vice versa [10]. Horizontal integration brings economies of scale and allows both sectors to compensate the respective risks and volatilities in production such as stocks fluctuations in fishing and disease outbreaks in aquaculture. The possibility to provide a more diversified range of products brings advantages in marketing and is responding to the tendency by large retailers to concentrate supply sources. Finally, horizontal integration represents for many fishing companies an opportunity for expanding and overcoming limitations imposed by fishing quotas and limited entry programs.

On the input side the use of fishmeal and fish oil by the aquaculture industry represents a highly debated issue with a series of diverging views. The exceptional growth of aquaculture is seen by some as a solution to relieve the pressure on fish stocks and contributing to food security, while others argue that the dependence of aquaculture from the small pelagic fish going into the production of fishmeal and fish oil is unsustainable from an ecological and ethical point of view and will ultimately represent a hindering factor for the expansion of aquaculture.

The aim of this paper is to review the interactions between aquaculture and fisheries at the food market level, in terms of resource use efficiency and in relation to the use of fishmeal and fish oil, examining different perspectives in the recent scientific literature. This analysis is contributing to the understanding of the implications of the important transition from fishing to farming which is characterising the seafood system and which could offer the opportunity to ensure food security, economic growth in rural and coastal economies, while at the same time relieving pressure from marine fishery resources. The analysis of the interplay between aquaculture and fisheries is important to develop integrated policies covering both sector such as the new European Common Fishery Policy which is assigning higher emphasis to aquaculture also in consideration of its role in promoting growth and jobs and diversification in coastal fisheries and aquaculture-dependent communities [11].

## 2. Food market interactions

Economic interactions between fisheries and aquaculture at the food market level have been described, among the first, by Anderson [12] in a theoretical market model for fish products. Anderson shows how the entry of aquaculture would lower fish prices, increase total supply and reduce pressure on overexploited fisheries managed under open access and exploited beyond maximum sustainable yield (Fig. 2). This leads to positive effects on the fish stocks and an overall improved economic efficiency of the fisheries. Although the model does not consider explicitly welfare implications it can be foreseen that the lower fish prices caused by the expansion of aquaculture may determine a profit loss for fishermen in the short term.

Ye and Beddington [13] described similar consequences considering dynamic interactions and two different substitution levels between farmed and wild fish. In the case of partial substitution market interactions are indirect and less evident

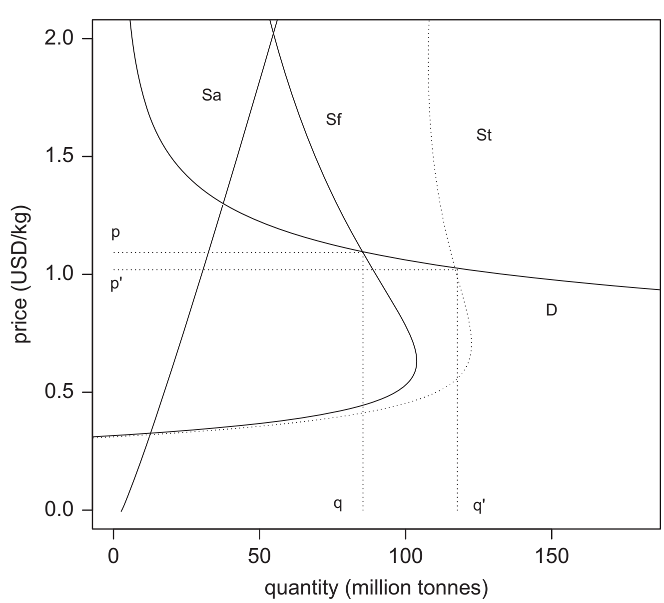


**Fig. 2.** Theoretical seafood market model showing the implication of the entry of aquaculture (price and quantities are illustrative and taken from Arnason [60]). Under the assumption of perfect substitution between farmed and captured fish, aquaculture supply (Sa) is adding up to the fishery supply (Sf) and generating a higher total supply (St). Given the backward bending shape of the fishery supply, the new equilibrium in respect of the global fish demand (D) results in lower prices (from p to p'), and higher quantity (from q to q'), which in turn implies lower fishing effort, higher fish stocks and in the short term lower profits for the fishermen.

but ultimately still producing lower fish prices and reducing the pressure on fish stocks. In both cases, of perfect and partial substitution, aquaculture is presented as an alternative to prescriptive management measures for reducing fishing efforts, with the additional benefit for the consumer of lower prices and increased supply. In conclusion social benefits are expected to be higher by adopting measures supporting aquaculture than by enforcing restrictive management on fisheries.

Asche et al. [14], using a stylised fishery bio-economic model, illustrated the different results from aquaculture development in relation to the characteristic backwards bending supply curve for fishery. The described effect of aquaculture in lowering fish prices is depending on the size of production relative to the size of the market in which it is competing. A strong effect can be observed in the case of farmed salmon where the production is large enough to condition the small wild salmon market, while a weaker effect is present for example between farmed shrimp and the larger wild shrimp market.

In the case of wild and farmed salmon in the US market a close substitution has been proved by econometric studies and the decline of prices of wild salmon since the 1990s has been clearly attributed to the rise of salmon production in Norway and Chile. Valderrama [15] analysed this case of strong market interaction and the repercussions of aquaculture development on Alaskan salmon fisheries. The analysis extends the initial model of Anderson [12], which was based on an open access fishery, by considering explicitly regulatory intervention and in particular restricted access and season length restrictions. The study reveals the contrast between the ability of Norwegian salmon industry to maintain profit margins by expanding production and lowering costs, and the economic inefficiency in the Alaskan fishery, in which investment and technology determine overcapacity rather than increasing productivity. In the case of regulated fisheries, fishing effort is bound to the limit of maximum sustainable yield and therefore the competition of aquaculture has little influence on the stocks; on the other hand, it is producing important and often neglected economic consequences for the profitability of the fishery.

In the described models the degree of market integration between farmed and captured fish has a key role in determining the level of interaction between aquaculture and fisheries. Market integration has been analysed for major aquaculture species and in particular for salmon, either by analysing demand functions or comparing causalities and correlation of price series through co-integration analysis and test for Law of One Price. After reviewing several studies on the integration between farmed and captured fish, Asche et al. [14] concluded that, with the exception of farmed and wild salmon, for most species there is little evidence of market interaction. It is plausible that the growing aquaculture production instead of competing directly with wild fish is finding new markets at lower prices and moving down the demand curve. Another explanation is that econometric methods are not powerful enough to detect integration or that aquaculture is competing simultaneously with multiple food products in such a way that interactions are less intelligible. The lack of interaction is considered coherent with the degree of segmentation of the fish market and explained through differences between farmed and wild fish within the supply chain and in terms of consumer preferences. Aquaculture differs from fisheries primarily for its ability to adapt production in response to market demand; thanks to an increased control on the production process it is able to supply the retail chain with larger quantities at the right moment and with homogenous characteristics responding to customer preferences for convenience food.

More recent studies give evidence of partial price integration for some species, which would indicate that the issue of market substitution between farmed and wild fish is depending from the product and market considered. Nielsen [16] analysed the trout market in Germany and indicated that while there is little competition with other farmed fishes and in particular with salmon, some linkages exist between trout and white fish of similar size like cod, halibut, redfish and mackerel.

Norman-Lopez [17] found that farmed fresh tilapia fillets in the US compete in the same market with wild fresh whole red snapper, fresh sea dab fillets and blackback flounder fillets. The most likely causes for this competition are that imports of tilapia are compensating for declining landings for these species and better responding to preferences by the consumers for convenience food and by the retail chains for having less volatile supplies in terms of prices, timing, quantity and quality.

In the case of white fish, where qualitative differences between farmed and wild fish are less evident, it is likely that species like tilapia and pangasius may compete directly on the same market with major whitefish wild species such as Atlantic and Pacific cod, Alaskan pollock, hake, saithe and more recent ones like hoki. Stronger market interactions may become evident in future, as the production of newer aquaculture species like barramundi and grouper will expand to a level capable of conditioning the market.

Consumer perception studies [16] have shown that while farmed fish is less favoured in terms of attributes of natural and healthy product, it has an image of being more respectful for the environment and contributing to the conservation of wild resources. As wild stock become overexploited, sustainability concerns may represent another reason for a shift of preference from wild fish to farmed fish, both for consumer and for buyers requiring large quantities of supply from sustainable certified sources.

With market interactions between farmed and wild fish becoming stronger the positive effects on fish stocks deriving from substituting part of the demand with farmed fish and the consequent implications on fisheries profitability and fishery management cannot be ignored anymore. Valderrama and Anderson [18] showed in reference to salmon in Alaska that these interactions may explain the lack of fishery management to realise an increase of rents and they conclude that the limited entry program should duly take into account the lower prices and consequent lower revenue determined by aquaculture competition. Although this case, given the size of production of the farmed salmon and the higher level of integration between farmed and wild salmon, may be considered emblematic, it seems plausible that similar effects of market interactions may become more common in future in particular in the whitefish and lower price aquaculture segments.

## 3. Environmental efficiency in the production of food

Another way of considering interactions between aquaculture and fisheries as sources of seafood is from the point of view of the environmental efficiency. This perspective brings insights in aspects that are not fully incorporated in prices and markets. The substitution and transition of an increasing part of the consumption of seafood from fisheries to aquaculture is obviously influenced by the available technological solutions/developments which may make these industrial sectors more sustainable.

As mentioned earlier, aquaculture is the most active food production industry in terms of growth rate with most of the production taking place in Asia and in particular in China. In recent years production has developed a more market-oriented attitude with a diversification between intensive and semi-intensive export oriented farming systems.

The expansion of intensive aquaculture production is accompanied by concerns and increased consumers awareness on the use of resources and the pressure on the environment, which brings the need for the industry to take measures for and prove the sustainability of its production. In this respect tools such as Life Cycle Assessment (LCA) are useful to address concerns of sustainability by comparing the load on the environment from different production systems according to a standard methodology.

Despite being fundamentally different production systems, fisheries and aquaculture can be compared using LCA in terms of energy use and green house gas emission.

The most important environmental impact in terms of energy use from fisheries is represented by fuel consumption, which depends from a number of variables, such as the gear type, trip length and distance to the fishing grounds, sea and weather conditions, icing and storage of the catch, etc… Vázquez-Rowe et al. [19] indicated how fuel consumption can vary substantially between purse seiners and coastal bottom trawlers targeting horse mackerel, with an average of 176 kg/t of fish in the first case and of 496 kg/t of fish in the second case.

Schau et al. [20] confirmed a clear trend of trawling to be more energy-intensive (from 0.32 to 0.78 kg of fuel/kg of fish) if compared to long lining (from 0.07 to 0.24 kg of fuel/kg of fish). In general, fuel consumption for demersal fisheries has been estimated to be from 300–660 l/t fish to 1500–2300 l/t fish, while pelagic fisheries would consume, depending on the species, from 100–150 to 1400–3400 l/t fish [21].

In terms of green house gas emission, Driscoll and Tyedmers [22] estimated an intensity of 65 $CO_2$ kg eq./t fish for purse seiners, of 337 $CO_2$ kg eq./t fish for mid water trawlers and of 365 $CO_2$ kg eq./t fish for pair trawlers. Green house emission for global fisheries have bee estimated by Tyedmers [21] in 134 Mt $CO_2$ eq. (i.e., 1.7 t $CO_2$ eq./t of product).

In the case aquaculture, values for energy consumption and carbon dioxide vary according to the level of technical intensification of the farming system, with higher values observed in the more energy demanding recirculation systems in respect of cages and pond aquaculture and with the greatest contribution to these impacts being represented by the input of feed.

Energy consumption has been estimated in 28,900 MJ/t (93.2% from feed) for salmon [23], 54,500 MJ/t (72% from feed) for sea bass, 78,200 MJ/t (40% from feed) for trout in flow-through systems [24] and 290,900 MJ/t (11% from feed) for turbot in recirculation systems [24]. In relation to carbon dioxide, the same studies indicate impacts, respectively of 2.15 t $CO_2$ eq./t for salmon, in 3.60 t $CO_2$ eq./t for sea bass, of 2.75 t $CO_2$ eq./t for trout, and of 6.01 t $CO_2$ eq./t for turbot. This is also confirmed in the study "Blue frontiers" [25] where the green house emission for global aquaculture production has been estimated in 350.89 Mt $CO_2$ eq. (i.e., 5.3 t $CO_2$ eq./t of product).

From the comparison of global figures of energy use and green house emissions aquaculture emerges as more input demanding than fisheries; however, it has to be considered that on one side fisheries are exploiting an open access natural resource with the main input being fuel while on the other side aquaculture is transforming feed into fish in a controlled environment. Given this key distinction a more balanced comparison would need to include the use of biotic resources, which in fisheries is directly measured by the volume of catches and in aquaculture deriving from the utilisation of fishmeal and fish oil in feed. According to Vitousek et al. [25] humans use approximately 7.2 billion metric t of organic matter which represent nearly 3% of annual biosphere's net primary productivity; the appropriation from fisheries is estimated in 2 billion t corresponding to 2.2% of marine production. The appropriation of biotic resources by fisheries has a direct impact on the status of fish stocks and according to latest FAO figures [1] is resulting in 53% of global fish stocks being fully exploited, 32% overexploited (28%), depleted (3%) or recovering from depletion (1%) and only 15% moderately exploited (12%) or underexploited (3%). While aquaculture may contribute on one side to alleviate the pressure from fisheries by substituting partly the demand for seafood, on the other side, it contributes indirectly to the negative impacts on the biotic resources since it is consuming a great amount of the almost 36% of landings going into the production fish meal and fish oil. This aspect as described in the following chapters is still one of the most controversial environmental concerns about the sustainability of aquaculture.

## 4. Interactions from the use of fishmeal

This issue of the fish meal use by aquaculture can be analysed considering four interlinked aspects: the evolution of use and prices of fishmeal and fish oil, the ecological sustainability of small pelagic fisheries, the ethical and economic concerns of using small pelagic fish for feed instead of food for the poor, and the technical viability of replacing fishmeal and fish oil with alternative ingredients in feed formulations.

### *4.1. Fishmeal and fish oil use and prices*

In a review Tacon et al. [26] predicted a decreasing inclusion of fishmeal and fish oil in aqua feed due to a combination of economic and market factors, while in another study Jackson [27] expected rather an increase in the use of fishery products in aqua feed.

More recent figures from the International Fishmeal and Fish oil Organisation (IFFO) indicate that global production of fishmeal and fish oil is stable, use of whole fish in feed is decreasing and the use of fishmeal and fish oil in aqua feed is increasing compared to poultry and pig feed [28]. In 2009, around 63% of fishmeal and 81% of fish oil went into aqua feed. Fishmeal is almost equally split between feeds for salmonids, marine fish, crustacean and other species, whereas more than 2/3 of fish oil went into salmonids feeds and around 20% into marine fish. According to IFFO, by-products from marine fish processing are increasingly transformed into fishmeal, having reached in 2009 a share of 25% of the global fishmeal production of around 4.8 million tons. By-products from fish processing and by-catch still face a number of limitations for feed processing, regarding the availability of the by-products, composition of the resulting meals and reverse effects of some ingredients, which may hinder a higher share in feeds. It has to be seen how the discard ban for European fisheries proposed in the new European Common Fishery Policy will increase the availability of by-catch for reduction.

For Naylor et al. [29] a continuous increase of production of pescivorous species could drive up the demand for forage fish unless substitute forms of oil are used. On the other hand production data indicate that salmon and other finfish aquaculture will not continue increasing at recent rates [30]. For the period from 1966 to 2005, the rate of growth in production of all finfish aquaculture peaked in 1984, and is declining since then at the rate of 0.34% per year. An even stronger decline of 1.2% per year in growth rates was observed in the highly fishmeal and fish oil reliant global salmon aquaculture. According to Liu and Sumaila [30], some of the reasons for the slowdown of growth rates are the scarcity of suitable space, changes in market conditions such as price drops, the scarcity and costs of feed inputs, environmental challenges resulting in stricter regulations, and increasing consumer awareness in food safety and quality of farmed products. For most regions, growth rates for aquaculture production are predicted also by FAO [1] to slow down, a trend observed already in China (average annual growth rates of 5.4% since 2000 compared to 17.3% in the 1980s and 12.7% in the 1990s), Europe and North America (average annual growth rates since 2000 of 1.7% and 1.2%, respectively). Data from FAO on the global aquaculture production show from 1999 to 2009 a much stronger growth in herbivorous species (mainly cyprinids) than in piscivorous species (mainly salmonids, sea bream and sea bass) (Fig. 3). In prawn production, the global growth from 1999 to 2009 was much stronger for the more omnivorous *Litopenaeus vannamei* when compared with the pescivorous giant tiger prawns *Paneaeus monodon*.

In general terms, aquaculture of a new species is initially more resource intensive and when successfully established, with its further growth there is an increase in efficiency, specialisation and productivity gains. Asche [4] showed on the examples of salmon and shrimps, that this process of intensification is a function of industry size. The increase in efficiency is especially apparent from the usage of feed. The percentage of fishmeal and fish oil in the compound feeds had a clear downward trend, e.g., for salmon from 45% fishmeal and 25% fish oil in the compound feeds in 1995 to estimated 18% fishmeal and 12% fish oil currently.

This trend is also shown by Tacon and Metian [31] in a global overview of feed uses. Between 1995 and 2006, the level of inclusion of fishmeal and fish oil, measured through the fish in/fish out ratio in compound feeds (FI/FO), was steadily declining for most farmed species (Fig. 4) while international prices of fishmeal and fish oil were increasing.

Price interactions between fishmeal and soybean meal have been analysed to understand if the two commodities can be considered substitutes. The possibility of substituting fishmeal in aquaculture would indicate on one side that aquaculture development is not likely to be hindered by the limited availability of fishmeal and on the other side that the demand of fishmeal determined by the exceptional growth of aquaculture is not likely to cause an excessive pressure upon small pelagic fish stocks.

Asche and Tveterås [32] used co-integration analysis to study the relationship between prices for fishmeal and other oil meals in the period 1981–1999. The analysis showed that prices followed

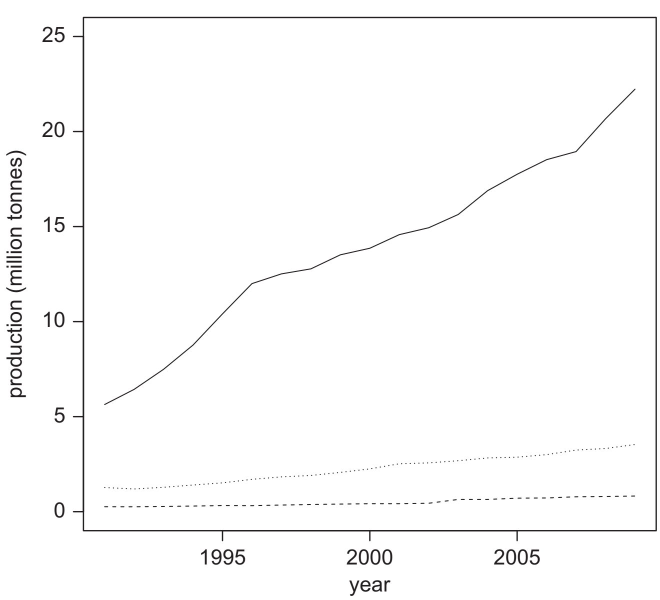


**Fig. 3.** Amount of aquaculture production for cyprinids (solid line), diadromous fish (dotted line) and marine carnivorous fish (dashed line) (source: FAO). Most of global aquaculture production and highest growth rates are registered by cyprinids for which the use of fishmeal is not indispensable but rather determined by the relative prices in respect of alternative ingredients like soy meal.

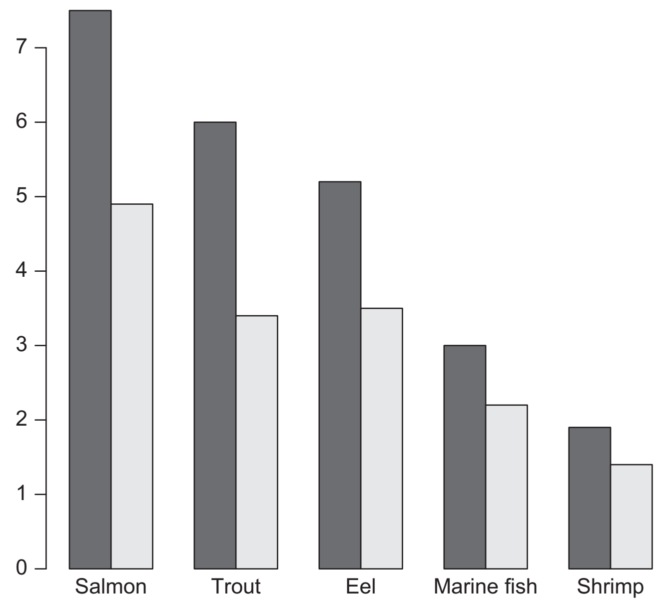


**Fig. 4.** Comparison of fish in—fish out ratio (FI/FO) between 1995 (dark grey) and 2006 (light grey) (source Tacon and Metian [31]). The reduction in the FI/FO is a sign of the structural change of demand: with relative prices for fishmeal and fish oil increasing their use is targeted at segments of the industry and stages in the production process where they are more indispensable and in parallel there is a stronger incentive for the industry to use alternative ingredients and improve feed efficiency.

the same stochastic trend and therefore fishmeal and soybean meal could be considered strong substitutes. This finding allowed drawing the positive conclusion that aquaculture growth would not lead to price increases and increased fishing pressure.

Kristofersson and Anderson [33], by analysing prices of fishmeal and soybean meal between 1978 and 2004 confirmed a stability of relation and substitutability only until 1998. Afterwards this relation ended and a structural change in the market was detected with increasing relative prices of fishmeal in respect of soybean meal. On the other hand, they observed that the fishmeal use predicted under the pessimistic assumptions of Naylor [7] was not coherent with a lower actual use of fishmeal in aqua feed and therefore that the growth of aquaculture could not be considered enough to explain the market structural change. An explanation of the market change was that an increased demand by aquaculture was partly compensated by a substitution within the aquaculture industry while in parallel there was an increased demand from the pig and poultry industry, which significantly contributed to an increase of fishmeal prices relative to soybean meal.

Asche [4] recognised that increased fishmeal prices would limit the growth of aquaculture of carnivorous species due to a stronger dependence from fishmeal, however he also underlined the fact that most of the global aquaculture production is based on herbivorous species and that in the case of salmon the technological development has already almost transformed this species in herbivorous.

In another study, Merino et al. [34] argued that the influence of aquaculture on fishmeal prices should be re-considered since the use for aqua feed has increased from 35% considered by Asche and Tveterås [32], to an estimated 70% in 2010. Under this condition the influence of aquaculture on fishmeal demand would be much greater. Using a bio-economic model for global fishmeal market and industry, they showed that a combination of negative effects from El Niño and sub-optimal management of fisheries would lead to a collapse of the fisheries of small pelagic fish.

Although apparently diverging, the different views seem to describe the same market phenomenon which is showing its effect in particular in the last decade. Since the fishmeal and fish oil market is quickly evolving in parallel to the exceptional growth of aquaculture, the period for which figures on production and prices are considered is an important determinant for the difference in views. While Jackson [35] was indicating that prices were remaining relatively stable against alternative ingredients, latest figures on prices (Fig. 5) seem to confirm that the divergence of prices between fishmeal and soybean meal is definitely taking place. However, in order to understand better if and how aquaculture demand may have contributed to this increase of prices there is the need to consider also other determinants such as the global economic crises, the prices of energy, the demand of soybean meal by the livestock sector and El Niño events to which stocks of small pelagic fish are particularly sensitive.

### 4.2. Ecological sustainability of the use small pelagic fisheries as forage fish

When describing the negative effects that aquaculture has on the world fish supplies Naylor et al. [7] listed the increasing use of wild fish for aquaculture feed, habitat modifications, the collection of wild seed stock and other ecological impacts, such as food web interactions, introduction of exotic species and pathogens. They concluded that aquaculture has to become more sustainable to contribute to the world fish supplies, in particular by reducing fishmeal and fish oil inputs in feed and adopting more ecologically sound management practices.

Tidwell and Allan [36] objected to this criticism by affirming that the ecological threat of aquaculture is much lower than continuing to use animal protein from wild captured fish. Their main argument is that the feed efficiency of farmed species is greater than in wild fish and likely to improve further with technological development. In addition, they consider that the dependency from fishmeal is mostly limited to salmon and shrimp which constitute only a relative small part of aquaculture production, that despite aquaculture growth, fishmeal production is not increasing, and that fishmeal demand could be met by better use of by-catch.

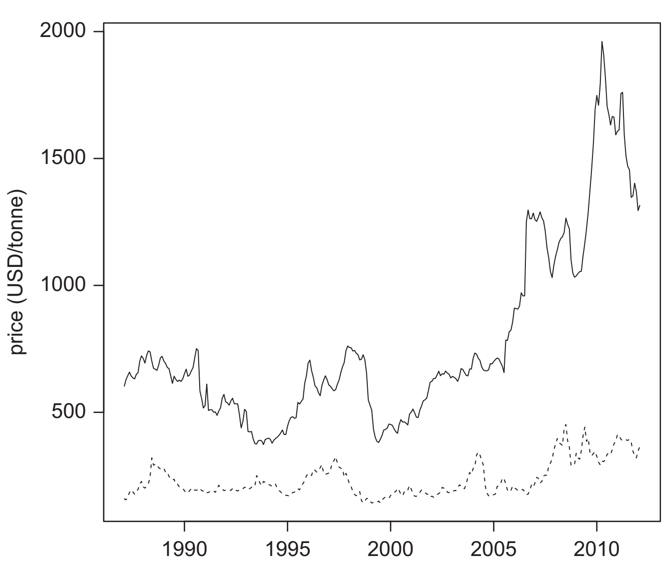


**Fig. 5.** Fishmeal and soybean meal monthly prices (source: World Bank [61]). While until 1999 co-integration analysis was indicating substitution between the two commodities, more recent data show a divergence in trends with increasing prices for fishmeal. A possible explanation for this divergence is the growing demand from aquaculture, although, effects from other factors, such as the demand from the livestock industry, economic crises and El Niño phenomena, should also be taken into consideration.

Several authors tend to distinguish the increased demand from aquaculture from its negative consequences on the small pelagic fish stocks. While the prices increase may determine a stronger pressure on the exploitation of the natural resource, the foreseen negative ecological impacts will be ultimately determined by the capacity of governments and fisheries to manage in a sustainable manner fishing activities. A number of studies highlight the need for forage fisheries to be managed in a sustainable manner to remain viable [1,29,37,38]. The relevance of sustainable fishery management has been recognised by the aqua feed industry which is moving towards voluntary sustainability certification schemes. This objective is pursued through product certification and labelling scheme, such as the Marine Stewardship Council (MSC) standard for sustainable fishing [39], the FAO Code of Conduct for Responsible Fisheries [40] or through the IFFO Global Standard for Responsible Supply [41].

The IFFO Global Standard for Responsible Supply is aimed at demonstrating the use of sustainable raw material by processing plants in the fishmeal industry. It is a business to business standard in which the reduction plant has to demonstrate the responsible sourcing, e.g., that the whole-fish raw material derives from fisheries managed according to the Code of Conduct for Responsible Fisheries, not from illegal, unreported and unregulated fishing and that fisheries by-products were not sourced from species on the IUCN Red List of Threatened Species.

In addition to certification schemes, the sustainability of marine fisheries and seafood markets has also been considered by a number of independent initiatives aimed at scoring performance of countries in relation to sustainable fisheries [42], aquaculture [43] and seafood markets [44]. These indicators may be further developed in particular in order to incorporate trade offs between aquaculture and fisheries to become useful tools for identifying best practice of environmental and socio-economic sustainability.

### 4.3. Fish for feed instead of food

According to Alder et al. [9], the current regional patterns of decline in human consumption of small pelagic fish in Africa, Oceania and America, suggest a direct competition between human consumption and forage fisheries. The use of small pelagic fish as forage fish is criticised because little is known on the impacts of its removal from the feed web on the ecosystem and because small pelagic fish is seen as contributing to food security and poverty alleviation. On the same line Metian et al. [45] indicate that feed use of small pelagic fishes competes with the use for food especially in developing countries where there is a strong dependency from fish as primary and low cost source of animal protein. Metian et al. advocate for limiting the use of small pelagic fish in feed especially in countries where the rural poor can consume it as food.

A more articulated view on the issue is given in a report by FAO [37]. The report is indicating that despite there is scope to switch feed fish to food uses, this would depend upon affordability and development of low cost conserved products. While there are possible benefits of switching at least part of the catches of forage fish to food in South American countries, in Asia there is a less clear cut, since cheap fish and trash fish contribute to the development of small-scale aquaculture, which has also positive effects on livelihood and human consumption. In sub-Saharan Africa the effects would be limited since feed fisheries are an exception and aquaculture is not yet developed and in any case not dependent on compound feed. In conclusion, a regional approach would be needed to assess the consequences of using more feed fish for human consumption.

A liberal view on the issue is given by Wijkström [46] who claims that using small pelagic fish as forage fish would not reduce the amount of fish available for human consumption, since most of the food grade fish used for feed has no alternative market as food. Only a limited portion of total catches of forage fish in Peru could be used as food locally; the rest would need to be canned and transported elsewhere with excessive costs. The possibility of providing income and employment through aquaculture development and in the feed fish industry is considered a more appropriate option to address the needs of the poor rather than subsidising the transformation of the catches of small pelagic fish into canned food and exporting the excess not used in the domestic South American market to Africa.

### 4.4. Substitution of fishmeal in feed formulations

The growth of aquaculture has been accompanied by technological developments, especially in respect to nutrition and genetics/breeding, which are moderating the pressure on the demand of fishmeal and fish oil. Currently, farmed salmon need significantly less feed than wild salmon to reach the same weight [47–50].

Important steps have been achieved by genetics and strain selection reducing the feed conversion ratio (FCR—total feed fed/total species group biomass increase). For most species groups included in the overview of Tacon and Metian [31], the gains in estimated feed conversion ratio between 1995 and 2006 are evident, e.g., for shrimp from 2.0 to 1.6, for salmon and trout from 1.5 to 1.3, and for Chinese carp species from 2.0 to 1.7.

Increasing knowledge on nutritional needs of the most established species in aquaculture enabled a partial replacement of fishmeal and fish oil in the diets [31,51–58].

Fishmeal and fish oil are used nowadays more and more as strategic ingredients at lower levels and for specific stages of production, e.g., in fry. The efforts for fishmeal and fish oil replacement are ongoing and further improvements are expected.

There are differences in the ability of different aquatic animals in synthesising highly unsaturated fatty acids (HUFAs), such as eicosapentaenoic acid (EPA) and docoshexaenoic acid (DHA), which determine the dietary value of fish in human nutrition as they are almost completely absent in higher plants. Such differences appear to be species and stage dependent. While many carnivorous species are incapable or inefficient in synthesising HUFAs from precursor long chain fatty acids, many freshwater and diadromous (forage fish) species have this capability [53,59]. These differences are reflected in the feed formulations for different species. Commercial feed contains for salmon around 18–24% of fishmeal and 12–16% of fish oil, for carps around 3% of fishmeal and no fish oil, for shrimp 12% of fishmeal and 2% of fish oil [31]. Naylor et al. [29] showed for Atlantic salmon, that a reduction of 4% of fish oil in the feed would lead to decline in FI/FO from 5.0 to 3.9, whereas the same reduction in fishmeal would have a much more moderate impact on FI/FO from 5.0 to 4.8. According to Naylor et al. [29], in particular the demand of fish oil is likely to determine aquaculture's absolute demand for marine resources and hence its role in conserving or depleting wild fisheries in the future.

Olsen [38] argues that the difference in species to synthesise HUFAs may drive global aquaculture towards species with low HUFA requirements. On the other hand, to avoid HUFAs to become the main constraint for developing intensive carnivore aquaculture, additional or alternative sources of HUFAs for fish feed have to be explored. Among the proposed alternative sources [29,38] a possibility is seen in large marine zooplankton stocks, as Antarctic krill (*Euphausia superba)* and copepod *Calanus finmarchicus* (red feed) that are found in abundance. From 10 to 20% of zooplankton production would represent a resource comparable to the annual global landings of pelagic forage fish. Replacing fishmeal and fish oil by zooplankton would have the advantage of moving cultured carnivore fishes one trophic level down; however, little is known on the role that Antarctic krill and red feed have in the ecosystem for fish, seabirds and marine mammals. According to Olsen, zooplankton might be a short-term solution for an expansion of mariculture if it can be exploited with acceptable consequences for society and the marine ecosystem. In longer terms, genetically modified plants, specific strains of macroalgae, mircroalgae, bacteria, yeast and other HUFA rich microorganisms could be exploited in culture. While GMO plants would compete in space with other agriculture productions and could face objections by consumers, the others are almost unexploited resource which could partially use waste deposits for growth and also contribute to the protein and energy supply in feeds. Olsen sees a main priority in the coming decades in developing the technologies to make such HUFA-containing products available.

## 5. Conclusions

Theoretical fishery economic models show how the expansion of aquaculture is determining lower fish prices and shrinking in the short term the profitability for the fishing industry. These models are based on the assumption that farmed fish and captured fish may be considered substitute products. The issue of substitution has been investigated by econometric studies and results are diverging according to the market and products considered. With poorly differentiated products, as in the case of processed seafood and white fish, the substitution has been more clearly demonstrated. With the expansion of aquaculture supply from industrialised production systems at low prices and a ceiling for the exploitation of fish stocks it is likely that the fish market will become increasingly segmented, with wild fish going into higher price segments and farmed fish into processed products channelled through the large distribution. Especially in the lower price segment interactions between aquaculture and fisheries are likely to become more evident in the future.

Regardless of how integrated markets are, processing and marketing of seafood can be considered similar for all fish. This brings significant synergies for companies in operating in both fishery and aquaculture sector. A diversified source of raw material attenuates the specific risks related to each sector and a diversified range of products gives to companies an advantage when serving customers. In addition horizontal integration brings economies of scale and opportunities for fishing companies to expand overcoming limitations imposed by fishery management.

The interactions between aquaculture and fisheries need to be considered also from the resource efficiency point of view. With an increasing awareness of consumers on the environment there is also an increasing demand for environmentally sustainable food and this is already translated into dedicated marketing decisions by major retail market chains.

The majority of the aquaculture systems perform better than fisheries or in a comparable way in terms of energy consumption and of carbon dioxide emissions. However, when considering the contribution of different production systems to global fish production and the input of feed, aquaculture seems more intensive than fisheries.

The main environmental advantages from aquaculture are not necessarily linked to energy efficiency but need to be evaluated also in relation to the consumption of biotic resources, which is on one side linked to the direct appropriation by the fisheries of the natural and open access resource of fish stocks and on the other side to the feed use in the more controlled but also more input demanding farming system. When considering aquaculture and fisheries interactions and the transition from one production system to the other from an environmental perspective, the key issue to be further investigated is the balance between the positive impacts linked to a reduced direct appropriation of biotic natural resources for human consumption and the negative impacts linked to the use of captured pelagic fish in feed, the emissions and effluents and escapees.

The issue of fishmeal and fish oil use from aquaculture is continuing to raise diverging views. At the feed market level, the increased demand from aquaculture is producing a divergence in prices trends between fishmeal and soybean and is pushing for a substitution with alternative ingredients. Market substitution and technological development, which open the choice for new ingredients and different sources of raw material, are counterbalancing the increased feed demands from aquaculture expansion. At the moment it is not clear how these counterbalancing forces will keep pace with aquaculture growth. It is likely that as substitution possibilities will be exploited, prices will start to determine an increase of costs and decrease of supply in the portions of the aquaculture industry where the substitution is not technically feasible. According to the more optimistic views this portion should be limited to few carnivorous species and for those species at specific stages of the production cycle, while great part of the aquaculture industry would be able to revert to substitutes without significant increases of costs. The implications in terms of ecological sustainability linked to the use of fishmeal can be simplified into three diverging views: the most concerned foresee an increased pressure on fish stocks from aquaculture growth; some authors tend to distinguish negative consequences on the fish stocks from aquaculture development itself, while the optimists see in the use of fishmeal for aquaculture a more efficient way of using resources in respect of the final goal of global supply of food. The ethical concerns in terms of food security for the poor relate to the more general discussion on the role of global food trade and the inter changeability between income generation and food accessibility. In this respect, general organisations like FAO seem inclined towards a more articulated view which, with the duly consideration of geographical differences, sees also positive elements in the income generation potential arising from the use of fishmeal according to destinations determined by the global market.

Overall this review, by summarising the main elements and views on aquaculture and fisheries interactions, indicate the importance of incorporating global fish market analysis in the modelling of economic profitability of fisheries, of assessing the compensation between the two production systems in terms of the different environmental impacts, of investigating further the use and price determinants of the fishmeal and fish oil market and developing global performance indicators taking into account the interplay and trade offs between the two industries as part of a single seafood market. These needs are important in terms of scientific support to policy development in particular in cases like the new EU Common Fishery Policy that is starting to consider the two sectors of aquaculture and capture fisheries in a more integrated way in terms of socio-economic development goals.

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