

## SUBSTITUTABILITY OF FISHMEAL IN DIETS FOR SALMON: AN OPTIMISATION BY SIMULATION APPROACH

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### ABSTRACT

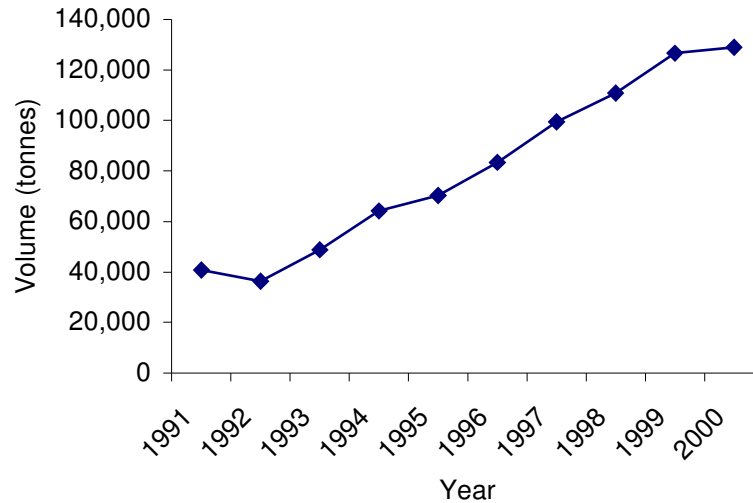
The world's output of farmed fish has grown steadily over the past two decades or so. Most notably in the UK, since the mid 1980's, a rapid increase in farmed salmon production has taken place. Given that many of the world's oceans are overfished, many see aquaculture as a method of feeding the world's growing population. However, the production of salmon relies heavily on marine raw materials as inputs in compound feed. Consequently, the demand for fishmeal is, therefore, increasing, although the production of fishmeal has remained relatively stable over the past decade or so suggesting that fishmeal has reached a production limit, with most industrial fisheries classified as fully or over exploited. Therefore, given the stagnant production from industrial fisheries and the rapid increase in aquaculture production, fishmeal can pose a biological constraint on production and thus aquaculture's contribution to world supplies. In this study, the economic feasibility of substituting fishmeal in diets for salmon was analysed through an optimisation by simulation approach using @Risk to derive range of combinations stochastically. The results indicate that there are cost combinations of alternative ingredients that can substitute fishmeal producing market size salmon for a similar price to traditional fishmeal diets.

**Keywords:** salmon, fishmeal, substitutability, simulation

### INTRODUCTION

Since the early 1980's production from capture fisheries has stagnated or even tended to decline. The overfishing problem is an international phenomenon and there is little indication that production from the world's capture fisheries will increase in the future, at least in the short term. The world's population, however, continues to increase and is now estimated to be around 6 billion and in excess of 1 billion people worldwide rely on fish as their main source of dietary protein. While this is not the case in developed countries demand is high because of the dietary virtues that fish offer (they are generally seen as a healthy source of protein).

The worldwide decline in capture fisheries production has led to the birth and growth of intensive aquaculture, which continues to grow as a result of the increasingly intensified methods of production. This is reflected in the rapid increase in production (by volume) of farmed fish over the last two decades or so. Between 1987 and 1997, global production of farmed fish and shellfish more than doubled in weight and value, as did its contribution to world fish supplies. In the UK, salmon farming began in Scotland in the early 1980's producing around 550 tonnes in 1980. This had increased to almost 100,000 tonnes by 1997 and 145,000 tonnes by 2003. Over this 23-year period salmon aquaculture in Scotland has grown from almost nothing to the third largest producing country in the world with annual growth rates between 10% and 35% (see fig 1)



**Figure 1. Salmon production in the UK (1991-2000). Source: FAO Fishery Statistics 2003.**

Growth in salmon aquaculture can be attributed to technical progress, economies of scale, increased capital intensity, significant improvements in diet formulation and feeding and increased survival rates. The salmon aquaculture industry in Scotland has provided substantial socio-economic benefits in remote parts of Scotland (Highlands and Islands) facing the challenges of economic development, stabilisation of communities and loss of population [1]. Therefore, in recent times, aquaculture has grown from an industry in its relevant infancy producing very little to currently contributing over 25% of world fish supplies consumed by humans. Aquaculture is, therefore, seen by many as a method of alleviating pressure on wild stocks at the same time as increasing the world supply of fish suitable for human consumption.

However, the rapid growth in aquaculture has given rise to a number of environmental concerns [2]. Some forms of aquaculture (for instance salmon and shrimp farming) have the potential to degrade the natural environment through disease, habitat destruction, and organic waste. Perhaps the most pressing concern is the sustainability of using fishmeal in compound feeds, which may further deplete wild fish stocks. This, therefore, raises the questions: to what extent is aquaculture a net contributor to world fish supplies? Or to what extent it is adding to the overexploitation problem?

This paper focuses on the economic and technical feasibility of substituting fishmeal in diets for salmon given that salmon dominates production in the UK and is the most significant user of fishmeal in the world<sup>a</sup>.

### **Aquaculture and the fishmeal trap**

Marine aquaculture in Europe, particularly carnivorous production, generally has high protein demands, which historically have been met adding high levels of fishmeal to compound feeds. Fishmeal provides the bulk (35-40%) of the protein used in salmon feeds and while the inclusion

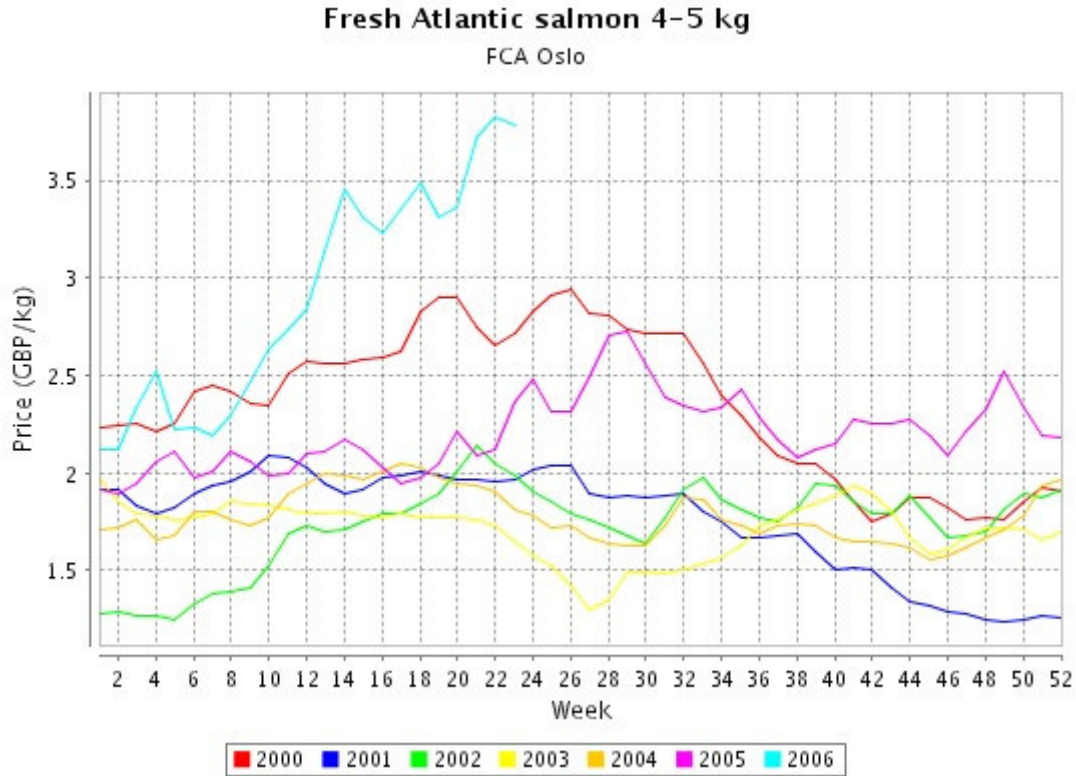
of fishmeal in diets has declined over the last decade or so, the demand for fishmeal has risen as a result of the industries rapid expansion. It is estimated that around 1/3 of world catches are reduced into fishmeal and oil, representing 80% of the oceans pelagic species. Projections for demand for fishmeal from aquaculture indicate the increasing scarcity and potential problems aquaculture's reliance on marine raw materials may pose in the future [see 3-5]. On the one hand, we have witnessed exponential growth in world aquaculture output, with many projecting a similar scenario in the future. On the other hand, production from industrial fisheries has remained stable over the past decade or so at 6 million tonnes of fishmeal and 1.2 million tonnes of fish oil. In short, the increasing demand for fishmeal in diets for farmed fish will lead to rapid increases in price, reflecting the scarcity of fishmeal, within the next decade or so [5].

Therefore, a further sustainable increase in farmed fish output can only be met through either diversion of inputs from other sources or through substitution with a suitable replacement. Historically, agriculture was the main user of fishmeal in formulated feeds but it seems that fishmeal is being directed from pig and poultry culture, as substitution is relatively straight forward, mainly to salmon and shrimp farming at increasing levels as economic factors indicate (i.e. as price of fishmeal increases). In fact, fishmeal use in pig and poultry culture is expected to decrease significantly over the next few years; where as demand from aquaculture is expected to increase substantially. This view was challenged by Theil et al [6], who suggest that fishmeal is necessary in diets for pigs to maintain current levels of productivity and therefore there are no apparent reasons why agriculture will substitute fishmeal for poorer performing ingredients (apart from economic reasons but this will also be the case for aquaculture).

Marine raw materials are preferred to vegetable, and other protein sources, as they provide the necessary nutrients required by farmed fish. However, as fishmeal becomes increasingly scarce increased price may make farming of carnivorous species (especially, small-medium scale farming) economically unviable. Wijkstrom and New, 1989 [7]; first raised concerns of the fishmeal trap and consequently many authors have reviewed the potential substitutability of fishmeal for alternative vegetable proteins in diets for salmon.<sup>b</sup> However, the economic appraisal of alternative feeds represents a gap in the literature and deserves some attention because if alternative feeds are to be adopted commercially they need to be both technically and economically feasible.

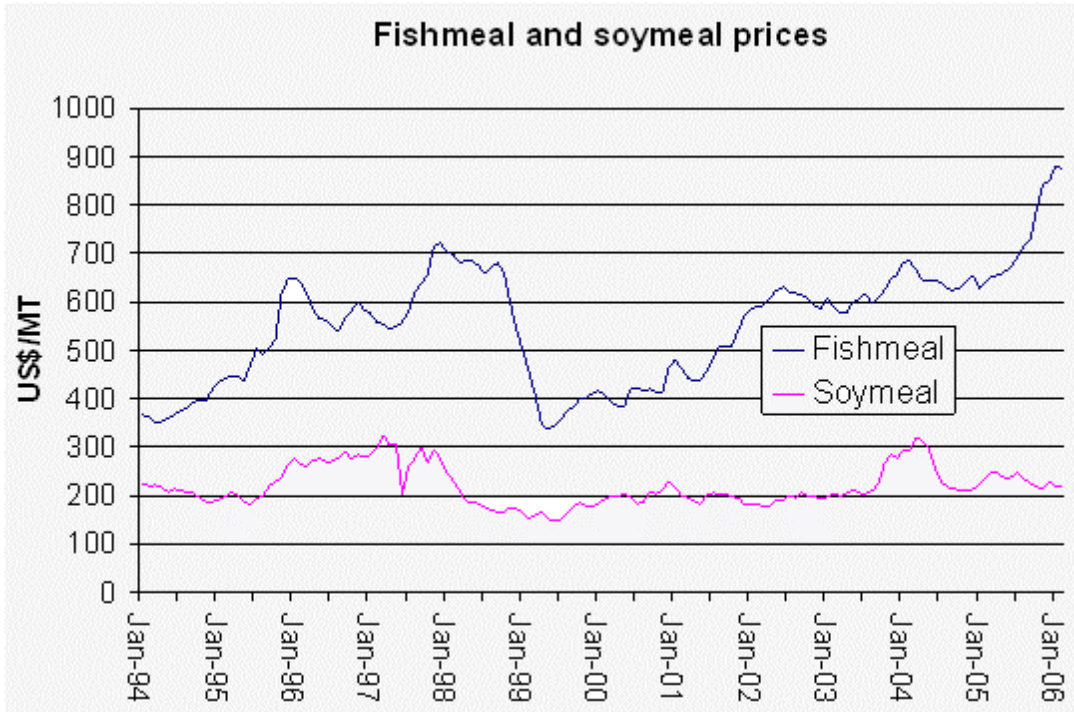
### **Why is economic appraisal important?**

Given that the production cycle of salmon is reasonably long (20-24 months) expected profits can change significantly dependent on the market (for example, some farmers may be forced to sell below marginal costs, because of cash flow constraints and irreversible production decisions made earlier in anticipation of the market). Salmon farming is characterised by periods of tight margins and low profits, but with intermittent periods of very high prices and large profits [11].



**Figure 2. Salmon prices (2000-2006). Source: intrafish.com**

Over the past few years the price of fishmeal has increased steadily, in part due to a steady decline in production but also increased demand from aquaculture, especially from China. Overall fishmeal production of the five major producing countries (Peru, Chile, Iceland, Denmark and Norway) reached about 3.4 million tonnes in 2005 compared with 3.6 million tonnes the previous year. China continues to be the main market for fishmeal absorbing record levels of fishmeal increasing 20% in the space of just one year. Demand for fishmeal is increasing almost everywhere a small increase in exports to EU-15 countries is visible and may be associated with the increase in carnivorous production. The gap, therefore, between fishmeal and vegetable protein price, most notably soymeal, is about four times. This does not, however, tell the full story, as there are significant costs associated with formulating diets including soymeal that are suitable and digestible by fish (i.e. amino acid supplementation). Nevertheless, assessment of the economic feasibility of substituting fishmeal in diets is important given that the price of fishmeal is only expected to further part company with the price of soymeal and other vegetable proteins (for example, in Chile, the horse mackerel quota has been reduced by 75,000 tonnes, which will decrease supply and further increase the gap between fishmeal and soymeal prices).



**Figure 3. Fishmeal and soymeal prices (1994-2006). Source: FAO GLOBEFISH**

Fishmeal price has reached new highs and has recently broken the US\$800 per tonne mark and although price is expected to drop slightly it is expected to stay above US\$800 per tonne.

Given the cyclical nature of the industry, as discussed earlier, it is possible that farmers operate at a loss during some periods of the production cycle and sometimes throughout a complete production cycle. As mentioned earlier, alternative feed compositions may increase the price of compound feeds given the higher formulation costs, although this may have less impact in the future as fishmeal price continues to increase. This does not mean to say though that either the cost of substitution/replacement or increased fishmeal price will be economically feasible in the short or long term for small-medium producers.

In this paper, two approaches are used to review both the technical and economic feasibility of substituting fishmeal in diets for salmon.

## METHODOLOGY

### Meta-analysis

To review the technical efficiency of substitution a meta-analysis production function was estimated. Meta-analysis refers to the statistical analysis of a large collection of results from individual studies, which typify our attempt to make sense of the rapidly expanding research literature. There are two types of meta-analysis: (1) those that use summary results from multiple studies and (2) those that use the raw data [12]. It is the latter method that was applied in this study to interpret the results of studies concerning the substitution of fishmeal with alternative feed sources.

Meta-analysis was used because each study in isolation considered a limited range of alternative ingredients but across the different studies a wide range of replacements has been considered. Meta-analysis was used to review the impacts on productivity of substitution with a wide range of alternative ingredients but also to review the variation in research results as it is understood that variation in growth can be explained by systematic variation in dietary design as well as methodological (stocking density and water temperature, for example) or unexplained study-level factors, which are captured in meta-analysis. This was important, as it is understood that there are a number of factors, other than the food fish eat, which contribute to how efficiently a fish grows. This may provide useful insight into the overall substitutability of fishmeal with vegetable proteins and provide alternative diet compositions that offer similar growth to today's high performing commercial feeds.

A production function was estimated relating the average growth per day of the fish to the feed level and composition. The production function describes the technical relationship between inputs and outputs of a production process, defining the maximum output(s) attainable from a given vector of inputs [13].

The model was estimated as a fixed effects translog production function of the form

$$\ln y_{i,j} = \beta_0 + \sum_f \beta_i \ln x_{j,f} + \frac{1}{2} \sum_f \sum_k \beta_{i,k} \ln x_{j,f} \ln x_{j,k} + \sum_{i=1}^{N-1} D_i + v_{i,j} \quad (\text{Eq.1})$$

where  $y_{i,j}$  is the observed average growth rate per day of treatment  $j$  in trial  $i$ ,  $x_{j,f}$  is the amount of feed type  $f$  used in treatment  $j$ , and  $D_i$  are a set of dummy variables representing the impact of the trial on growth (i.e. water temperature, starting size etc). The translog is a flexible functional form that allows both the growth elasticity and the elasticities of substitution to vary from one treatment to the next. The Cobb-Douglas production function is a special case of the translog production function, where all  $\beta_{i,k} = 0$ . However, the Cobb-Douglas production function imposes an implicit assumption that the elasticity of substitution is 1 for all inputs.

The results indicate for salmon that fishmeal is substitutable with alternative protein sources [see 14]. However, the results of the study indicate that current levels of productivity could not be maintained feeding a diet based on vegetable proteins but this does not indicate that fishmeal cannot be substituted in diets for salmon. This is an important consideration for two main reasons: (1) salmon farmers in the UK have, over the past few years, been making very little, if any, profit and (2) given the high control supermarkets have regarding price determination it is unlikely that farmers can expect to demand or receive a higher price for their product. In addition, when taking into account the increased feed formulation costs, as a result of anti-nutrients, adding attractants to feed, for example it is likely that new generation feeds have the potential to reduce productivity and profitability at the same time. Therefore, if alternative feeds are to be accepted commercially they must be both technically and economically efficient.

### Optimal mix of inputs

It was found that the translog model was too non-linear to derive economic optimal mixes using traditional techniques (e.g. Non-Linear Programming) and therefore this paper uses @Risk to derive ranges of combinations stochastically. The aim of this analysis was to derive optimal mix

of inputs (vegetable proteins) to grow fish when substituting fishmeal at different levels.<sup>c</sup> Therefore, we estimated days and cost to produce a tonne of fish incorporating feed costs and prices.

The analysis was conducted and optimal mixes derived using the @Risk simulation model across 1000 iterations with different combinations of parameter values. The model used a stratified sampling technical (Latin Hypercube) as this is recognised a superior model to the traditional Monte Carlo simulation method in that it is more efficient in forcing convergence with a given number of samples [15]. Given the variable values are stochastic, we describe the nature of their uncertainty (defining probability distribution), assigning a range of values that the variable could take. The uncertain variable(s) is added as a probability distribution function, for example:

RiskTriang (min, most likely, max)

The goal of simulation is to derive a probability distribution that describes the possible outcomes of an uncertain situation and generate valid results, the results presented as probability distributions. For the purpose of this analysis, the results are compared to the stochastically derived mix that performs similar to a standard commercial diet.

## **RESULTS AND DISCUSSION**

Two simulation models are run in total. The first model is run minimising the level of fishmeal and oil in diets for salmon, as none of the scientific studies used in the meta-analysis attempted to completely replace fishmeal and/or oil. The second model was run with a fixed amount of fishmeal and oil (1/2 of typical fishmeal based diet).

The results generated by the @Risk simulation consider all possible outcomes (including least and highest cost combinations) and the probability they will occur. However, figure 3 indicates that whilst least and highest cost combinations are possible outcomes the probability of occurrence is less than 2% and therefore does not represent a risk.

Distribution for days/total cost

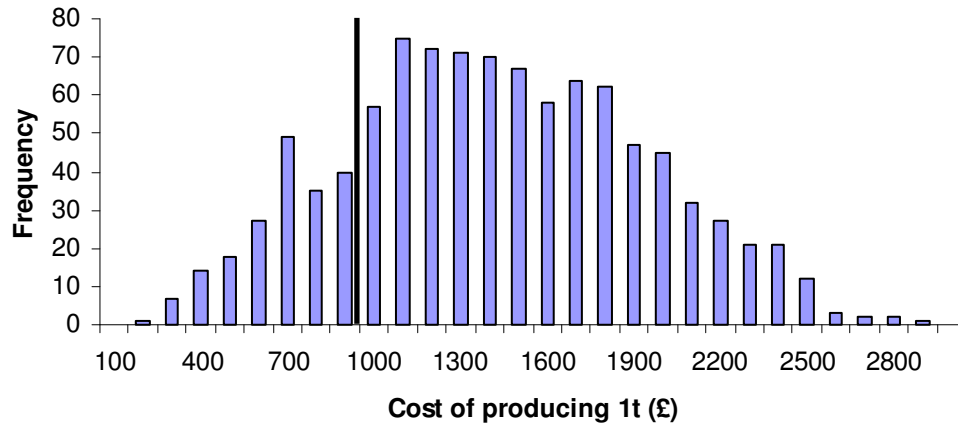


Figure 4 – Cost combinations

Given that we are trying to derive the optimal mix of inputs, we refer to the least cost combination, as this gives us the combination of inputs that can produce a tonne of salmon for the lowest price.

Table I: Least cost combination - £151

	days	fishmeal	fish oil	other	soy	wheat	vit+min	Total
original	609	2.300	1.624	0.644	0.449	0.763	0.087	5.868
"optimal"	468.254	0.059	0.037	2.260	0.527	1.732	0.013	4.628
increase	0.769	na	na	3.508	1.174	2.269	0.15	

The least cost combination of alternative ingredients was found to be £151. This is, however, probably unrealistic given the significantly decreased production cycle of 468 days, which is approximately 140 days less than current commercial production cycles. To achieve this level the “other” ingredients (other refers to the other vegetable proteins that made up the protein content of the diets but were not common to all treatments and therefore could not be included in the model) were increased significantly along with soy, wheat and vitamins and minerals. There are, therefore, concerns regarding the nutritional viability of the lower cost diets, given there is little empirical evidence suggesting both fishmeal and oil can be completely replaced in diets for salmon. In addition, the highest cost combination of ingredients was £2842, which is also considered unrealistic given it would be impossible to operate profitably as there is no expectation that market price will increase to take account of any decreased profitability at farm gate level.

The current cost of feed required to grow one tonne of salmon is approximately £985 (Scottish Agricultural College (SAC) Farm Management Handbook)) and therefore cost combinations between £800-1000 will be considered to assume economic feasibility. This suggests that there is a higher probability that fishmeal replacement diets will increase diet cost and thus operating



costs. Also, the results indicate that the production cycle will be increased contributing to the overall increased cost. Nevertheless, fishmeal price will rise in the future and therefore, in this scenario, the probability of least cost combinations would increase.

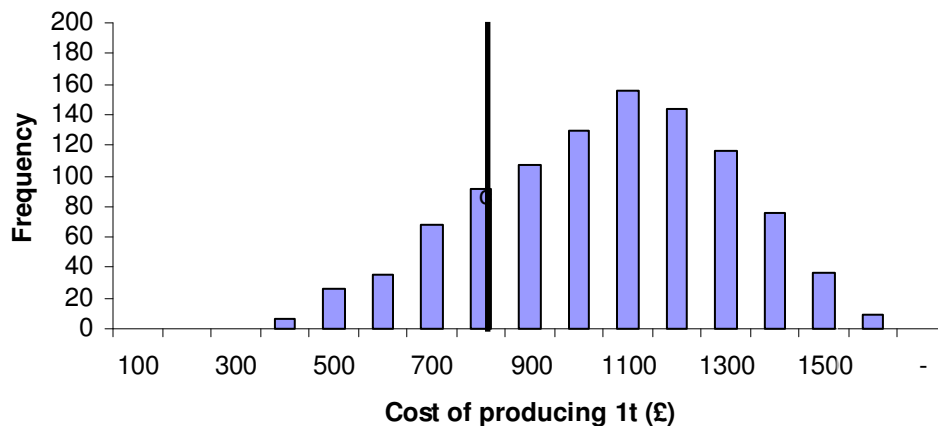
**Table II: Cost combinations £800-1000**

	days	fishmeal	fish oil	other	soy	wheat	vit+min	total
mean	599.164	0.059	0.037	1.984	1.214	2.101	0.170	5.47
stdev	95.465	na	na	0.803	0.503	0.986	0.032	
cv	0.159	na	na	0.404	0.414	0.469	0.189	
original	609	2.300	1.623	0.644	0.449	0.763	0.087	5.868
increase	0.983	na	na	3.080	2.703	2.753	1.947	

Considering cost combinations between £800-1000 indicates that when replacing fishmeal in diets for salmon all other ingredients in the diet need to be increased. In this case, “other” ingredients, soy and wheat were all increased by a factor of approximately three. In addition, the inclusion of vitamins and minerals was also significantly increased (factor of two), which would contribute significantly to diet cost even though they are only included in relatively small amounts.

Given much of the empirical research has focused on substituting fishmeal (rather than complete replacement) a second simulation was undertaken including 50% of the level of fishmeal and 50% of the level of fish oil included in a standard commercial salmon diet.

**Distribution for days/total cost**



**Figure 4 – Cost combinations**

As expected, the 2<sup>nd</sup> simulation indicates that there is a higher probability that the diet would cost more than a diet completely replacing fishmeal and oil (given fishmeal and oil are the two most expensive inputs in commercial diets). However, the worst-case scenario (i.e. high cost) is less for diets containing a fixed amount of fishmeal and oil, which can be a result of reduced production cycle.

The least cost combination when including 50% fishmeal and 50% fish oil (based on standard commercial diet) was found to be £346.

**Table III – Least cost combination - £346**

	days	fishmeal	fish oil	other	soy	wheat	vit+min	total
original	609	2.300	1.624	0.644	0.449	0.763	0.087	5.868
"optimal"	516.153	1.15	0.088	0.671	0.817	0.855	0.013	3.597
increase	0.847	na	na	1.042	1.820	1.120	0.157	

To achieve the least cost combination the production cycle was reduced to 516 (commercial diet 610 days). It is feasible that given further technological advances that a production cycle could decrease to 516 days but it is probably unrealistic, even with a diet containing fishmeal and oil. Based on the scientific studies used in the meta-analysis it is likely that an alternative diet will at least in the short run decrease growth rates (until further innovation/technical advances etc). Also, given the relatively high levels of fishmeal that will be included and that the production of farmed fish is expected to increase significantly, current market prices for fishmeal indicates that the least cost combination is probably unrealistic.

Cost combinations between £800-1000 indicate that the inclusion of other ingredients (other, soy, wheat and vitamins and minerals) needs to be increased by a factor of 1.7 to maintain current levels of productivity.

**Table IV: Cost combination £800-1000**

	days	fishmeal	fish oil	other	soy	wheat	vit+min	total
mean	594.911	1.15	0.881	1.096	0.719	1.188	0.127	5.161
stdev	46.093	na	na	0.402	0.279	0.459	0.018	
cv	0.077	na	na	0.366	0.387	0.386	0.145	
original	609	2.300	1.623	0.644	0.449	0.763	0.087	5.868
increase	0.976	na	na	1.702	1.601	1.556	1.459	

In addition, some of the higher cost combinations are potentially feasible given the reduced production cycles. Conversely, a number of diets with lower cost combinations result in increased production cycles, which will increase overall production costs but may be feasible given the reduction in feed cost. Perhaps most interesting are the cost combinations that are distributed close to the mean total cost but producing market size fish around 30-40 days quicker, suggesting they may be more economically efficient than today's high performing commercial diets.

In summary, the results presented here suggest that there are a number of alternative feed combinations that can substitute/replace fishmeal in diets for salmon.

## CONCLUSION

Aquaculture continues to grow into the new millennium and its share of the fishmeal market is expected to increase significantly. Aquaculture has the potential in the long-term to supplement catches from declining fisheries if further growth phases of growth are sustainable. Reducing demand for marine raw materials will, needless to say, contribute to sustainable development. Given that feed is the most expensive input factor of production (approx 60% of total production costs), farmers will be keen to replace fishmeal dense diets providing cost and productivity combinations of alternative feeds do not in the long run significantly effect profitability. Given the production of fishmeal is limited and further increase in aquaculture output is expected use of fishmeal in diets the price of fishmeal will raise and it will not be feasible to farm salmon feeding conventional feeds. At this time alternative feeds will become more appealing and will be necessary for further expansion.

The results suggest there are combinations of alternative ingredients that can substitute fishmeal in diets for salmon. However, as demand for fishmeal increases so to will price and thus industrial fisheries will become economically appealing and fishing effort will increase. In turn the price of fishmeal and vegetable proteins (especially soy meal) will further part company to the point where alternative diets become economically appealing assuming reduced productivity. In conclusion, this paper has demonstrated that substituting fishmeal in diets for salmon can potentially be technically and economically feasible, suggesting that the adoption of alternative feeds may give rise to a further sustainable increase in world aquaculture output.

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## ENDNOTES

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<sup>a</sup> In 1999, fishmeal use in aquaculture was dominated by 5 categories of species. Those were salmon (21%), followed by marine shrimp (19%), selected marine fish (10%), eels (9%) and trouts and sturgeons (8%)

<sup>b</sup> See Kaushik et al. (1995), Morris et al (2005), Thiessen et al (2004)

<sup>c</sup> No attempt was made to derive optimal mixes of inputs completely replacing fishmeal given this was not attempted in the scientific data used in the meta-analysis.