A model system to evaluate the economic performance of two different dietary feeding strategies in farmed Atlantic salmon (*Salmo salar* L.)

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Abstract

This paper evaluates the feed cost differences in salmon farming based on two energy dense feed strategies: one resembles the industrial preference of using high-fat diets (LP: low protein-to-lipid ratio) whereas in the other strategy the dietary energy is to a greater degree derived from protein (HP: high protein-to-lipid ratio). Two different economical models are presented based on three different feeding experiments: one commercial large-scale and two small-scale trials. All trials were conducted with year old smolt (S1). Production costs have increased from 2009 to 2016, and the presented data depict a general increase in price of feed proteins and oils. Dietary proteins are more expensive than lipids and in isoenergetic diets, protein denser feeds are higher priced than the lipid dense alternative. HP diets lead to a higher feed deposition in carcass which results in a significantly lower feed conversion rate compared to the preferred isoenergetic LP commercial diets. Because of the improved feed-to-carcass conversion, the HP feed strategy yields a lower feed cost. In addition, the HP feed strategy induces faster growth that that enables farmers to reduce the production cycle. A reduced production cycle represents an opportunity of reducing overall production costs. If improved growth is induced by dietary strategy, the reduction of overall costs should be assigned to the feed costs, i.e. a reduction of feed cost. Finally, dietary induced improvements in carcass weight yields more tradeable product which increases income. Thus, the present model system revealed that the traditional high-fat diets preferred in the salmon industry, although they are cheaper than the isoenergetic protein rich diets, are necessarily not precursors for overall lower feed costs.

Keywords: Atlantic salmon; feed cost; production cost; economic performance; dietary protein-to-lipid ratio

1. Introduction

Since the start of salmon farming in the 1970s, the industry has evolved quickly and developed into a modern intensive food production system (Asche et al., 2018a). Global production has increased from a few thousand metric tonnes in 1980 to approximately 2.4 million metric tonnes (FAO, 2018). From the start and through the 1980s, farmed salmon was mainly supplied to high-end markets as a luxury high-priced product. However, prices decreased towards the millennium following productivity growth in the industry (Asche, 2008; Kumar and Engle, 2016). This reflects the focus that has been in the industry on increasing production volumes to achieve scale advantages (Asche and Bjørndal, 2011). Such industrial competition typically results with a standard commodity where increased margins are achieved through cost reductions (Porter, 1980). Consequently, the majority of farmed salmon has been sold as fresh head-on gutted (HOG) salmon. Increased productivity and correspondingly lower prices repositioned salmon to become more available for other market segments as a competitive protein source relatively to other animal protein sources (Tveterås et al., 2012). Nevertheless, average HOG prices have seen an increase during the last decade as the demand growth seems to have been relatively higher than the growth in productivity (Brækkan et al., 2018), and several of the most important salmon producing nations experience restrictions on growth due to environmental concerns (Osmundsen et al., 2017).

Keeping salmon in controlled captivity throughout the production cycle has allowed systematic knowledge gathering and improvements with several factors that influence the overall productivity (Asche and Bjørndal, 2011). Feed is a crucial input factor and represents approximately 50 % of the total cost of production (Asche and Bjørndal, 2011). Like other production industries of animal protein, salmon farming is all about converting feed to food.

Compared to other aquaculture species and terrestrial animals, salmon is an efficient feed to food converter (Torrisen et al., 2011; Sarker et al., 2013). Salmon are carnivores and primarily utilize proteins and fats which are rich in energy. The cost focus in the industry has pushed the feed industry to compete on price, and although the cost share of feed has increased, the cost of feed has still been significantly reduced from the industry's early days.[1]

In line with enhanced nutritional knowledge and improved feed production technology, the energy in salmon feed has increased since the initiation of the industry (Tacon and Metian, 2009; Torrisen et al., 2011). The aquaculture sector has been a growing consumer of fishmeal and fish oil, and especially feeds for salmonids have relied heavily on the use of fishmeal and fish oil (Shepherd and Jackson, 2013). However, due to shortage and because of the foreseen necessity combined with an enhanced nutritional knowledge, these marine ingredients have been increasingly replaced by plant substitutes (Ytrestøyl et al., 2015; Aas et al., 2018). Concurrent with the development of energy denser diets, the fat content in the feeds has increased proportionally with a decrease in protein in the grower diets for salmon (> 1 kg), altering the dietary protein-to-lipid ratio significantly. Because plant proteins generally have lower protein concentrations compared to fishmeal (National Research Council, 2011), the shift towards high-fat diets has not only reduced the cost of energy in the feed, but also made it easier to use cheaper plant proteins. This has enabled salmon farmers to buy cheaper sources of dietary energy without compromising feed utilization and growth performance (Hillestad and Johnsen, 1994; Hillestad et al., 1998; Azevedo et al. 2004; Karalazos et al., 2007; Karalazos et al., 2011). However, these earlier results contrast the findings of Weihe et al. (2018), who reported both improved feed conversion and faster growth with a high protein-to-lipid feeding strategy. In addition, feeding salmon high-fat diets tend to increase the deposition of fat in both

[1] Sandvold (2016) depics a similar development for smolt.

muscle and visceral tissue (Einen and Roem, 1997; Hillestad et al., 1998; Jobling et al., 2002, Bendiksen et al., 2003, Weihe et al., 2018). Increased visceral weight might be considered as productivity loss as this tissue is of lower value than the HOG product. These findings suggest that the potential productivity increase caused by improved nutritional knowledge primarily has been taken out by providing cheaper feed, and not by improving growth performance. Nonetheless, the potential challenge of manufactoring high-energy protein derived feed based on plant proteins needs to be considered.

Because of its anadromous biology, the production of salmon is divided in to a freshwater phase and a seawater phase. An average total production time is approximately three years depending on the feed intake and subsequent growth performance, which are influenced by several biotic and abiotic factors (Houlihan et al., 2001). Continuous brood stock management, increased dietary energy and vaccine development are some key factors that have enabled the industry to produce salmon in high intensive conditions using tanks on land during the freshwater stage, and net-pens in the seawater phase. However, keeping high animal density in captivity increases the risk of spreading diseases, and in the case of salmon production, there are great challenges related to sea lice infestation as well as viral diseases which increase the cost of production due to increased mortality, reduced growth performance, treatment and use of higher priced functional feeds (Costello, 2009; Aunsmo et al., 2010; Martinez-Rubio et al., 2012; Martinez-Rubio et al., 2013; Torrisen et al., 2013; Martinez-Rubio et al., 2014; Abolofia et al., 2017; Iversen et al., 2017). Thus, keeping salmon with high density in captivity possesses a high economic risk, and it is of great importance that the production cycle is as short as possible. In contrast with the general feeding strategy in the salmon industry where high-fat feeds are preferred to more expensive high-protein diets, recent results demonstrate that a dietary high protein-to-lipid feed strategy can improve growth performance (Weihe et al., 2018). Although such a feed strategy can reduce the duration of the production cycle and associated risks, dietary energy derived from proteins sources are generally more expensive than dietary energy derived from fat. Hence, it is a potentially important question what the trade-off between cost and growth performance is. As prices of ingredients and the feed vary significantly, it is also possible that this relationship is changing over time.

The objective in this paper is to present a feed cost evaluation of two different isoenergetic dietary feeding strategies with either high protein-to-lipid ratio (HP) or low protein-to-lipid ratio (LP) from three different feeding experiments. Two of the experiments were completed in small-scale research facilities and the third one was a large-scale full production cycle in sea from stocking of smolts to harvest. The cost evaluation is presented with two different models: (1) a model based on the results from the small-scale trials, which only includes the direct cost of feed price and feed conversion into tradeable carcass and (2) a model which builds partly on model 1 and incorporates the value of reduced production cycle together with a potential value of increased share of tradeable product. These values are regarded as opportunity costs. Before presenting the results of these models, the development of some feed ingredient prices as well as price development in the salmon market will be presented.

2. Methodology

2.1 Experimental feeding strategies

The evaluation of economic performance using a dietary high protein-to-lipid feeding strategy (HP) versus a dietary low protein-to-lipid (LP) feeding strategy, were based on data from three feeding experiment conducted from 2009 to 2013. The first trial was completed in large-scale commercial conditions in the Faroe Islands with year-old smolt (S1), followed by two small-scale trials in controlled research facilities in Norway with S1 smolts (Fig. 1). The biological data used as foundation of the economic analysis in this paper where based on the previous results from Dessen et al. (2017) and Weihe et al. (2018) which presented data for feed utilization and growth performance in salmon fed either LP or HP feed. The small-scale trials were divided into three feeding periods (Table 3 and 4) whereas the large-scale experiment reflected a commercial production cycle from stocking of smolt in sea to grow-out until tradeable sized salmon (Table 2). The biological and economical evaluation of the small-scale trials was conducted for each feeding period as well as for the overall trial, whereas the large-scale performance was evaluated for the overall production cycle only.

The proximate composition of protein and lipid in the LP diets in all three trials were designed to resemble common commercial diets with majority of the energy deriving from lipids. The HP diets were designed to have similar energy as the LP diets but with a greater proportion of the energy deriving from protein. Although the aim was to produce trial feeds with equal digestible energy in each pellet size within each experiment, the dietary LP feeds contained somewhat higher energy than the HP feeds (Table 1). Havsbrún (Fuglafjørður, Faroe Islands) produced all the experimental feeds in all three trials. Feed production followed standard commercial feed manufacturing, which included monitoring of nutritional and physical quality throughout the production process. Following industrial practice, quality specifications and definitions of the feed ingredients were updated quarterly together with the respective raw material prices. This entailed that the experimental feeds used in the large-scale experiments originated from several production batches, whereas the feeds used in each feeding period in the small-scale came from a single production batch (Table 1). Based on the intended dietary protein and lipid balance, all feeds were composed and produced on a least-cost production strategy. The economic evaluations are based on the actual feed prices used during the trial periods. For further details about the feed experiment, see Dessen et al. (2017) and Weihe et al. (2018).

2.1 Biometric data

At trial initiation in the large-scale experiment, the mean number of the experimental fish was 66 883 ± 305 and the mean body weight was 104 ± 6 g. The feed trial started when the S1 smolts were stocked in the sea in April 2009 and continued until the fish reached commercial harvest weight (> 4 kg). In the first small-scale experiment, 8000 x 95 g S1 smolt were randomly divided into eight net pens in March 2012. Subsequently, the net pens were split into two quadrouple groups that were supplied with HP or LP feed through three feeding periods. In the second small-scale experiment, the HP fed salmon group from the small-scale trial were randomly restocked into six net pens in September 2012, 150 x 978 ± 1 g in each pen. Afterwards, these net pens were divided into two groups of three replicates to be fed the HP or LP feed. As with the first small-scale experiment, the second small-scale trial was also split into three feeding periods to assess the dietary influence on fish performance.

In the small-scale trials the fish were given daily feed rations which were approximately 10 % in excess of the feed eaten the day before. Waste feed was thereafter collected daily and analysed for recovery of dry matter (Helland et al., 1996; Einen et al., 1999). Because waste feed collection is not used in commercial farming, all distributed feed in the large-scale net pens was assumed eaten by the salmon.

At harvest, the experimental fish in the large-scale trial followed standardized harvesting routines of the respective salmon farming company. Thirty fish (10 fish from each weight class of 4.5 kg, 5.5 kg and 6.5 kg) from each experimental net pen were sampled at the harvesting facilities where body weight and carcass weight were recorded (Weihe et al., 2017) and harvest yield calculated. Based on the harvest yield, the final live biomass in each net pen was calculated based on the total carcass weight of all fish recorded at the harvesting facilities. In the small-scale trials, all fish from each experimental net pen were counted and bulk weighed of live weight and the end of each feeding feriod. Ten fish representing the mean live weight were measured for carcass weight to calculate to overal harvest yield, whereas during harvest in the second small-scale trial, as in the large-scale study, 10 fish from the weight clasess of 2.4 kg, 3.2 kg and 4.0 kg were sampled and measured for live weight and carcass weight and harvest yield calculated. This yield was used to calculate the overall mean carcass weight in each net pen based on the bulk weighing of live weight. The fish in the second small-scale trial did not reach the same live weight as the fish in the large-scale trial, and this explains why fish were sampled from different weight classess from the two trials. The final live weight and carcass weight in each of the three experiments were used to determine growth performance and feed conversion efficiency of the two dietary feeding strategies.

2.2 Industrial data

The industrial cost data are based on the annual profitability statistics of the Norwegian salmon industry arranged by Norwegian Directorate of Fisheries (Directorate of Fisheries, 2018; Table 5). Data for production cycles/time are based on industrial performance of the Faroese salmon industry (Avrik, 2018; Table 6).

2.3 Calculations

2.3.1 Fish growth

The growth rate of the fish is presented as the thermal growth coefficient (TGC) as described by Cho (1992):

(1) $TGC = (W_1^{1/3} - W_0^{1/3}) \times (\sum T)^{-1} \times 1000$,

where W0 and W1 are the initial and final live weight, respectively. $\sum T$ is the sum of day degrees during the period and is calculated as average temperature (C°) in the period x number of feeding days in the period. A higher TGC accordingly represents a faster growth rate and a shorter production period.

2.3.2 Feed conversion

The biological feed conversion ratio (FCR_{BW}) explains how much feed is consumed to produce 1 kg of live weight salmon:

(2) FCR_{BW} = feed intake (kg) x (biomass increase + biomass of lost fish (kg))$^{-1}$.

Carcass weight was defined as the weight after removal of blood, viscera, heart and kidneys. The biological feed conversion ratio based on carcass weight (FCR_{CW}) explains how much feed is consumed to produce 1 kg of head-on-gutted salmon (HOG):

(3) $FCR_{CW} = FCR_{BW} \times \text{harvest yield}^{-1}$,

where harvest yield is calculated as carcass weight/live weight.

2.3.3 Feed cost excluding value of transferable product and production duration (direct cost)

This section provides the basic model that does not account for the opportunity cost of faster growth.

The difference in the feed price is given as:

(4) FC_P = (price kg^{-1} of LP feed) – (price kg^{-1} of HP feed).

The difference in feed cost based on live weight is:

(5) $FC_{P\,BW}$ = (price kg^{-1} of LP feed x FCR_{BW} in the LP group) – (price kg^{-1} of HP feed x FCR_{BW} in the HP group),

while the difference in feed cost based on carcass weight is:

(6) $FC_{P\,CW}$ = (price kg^{-1} of LP feed x FCR_{CW} in the LP group) – (price kg^{-1} of HP feed x FCR_{CW} in the HP group)

In addition to calculating the feed cost differences within each period, the final feed cost difference for the whole trial was determined by calculating the overall weighted mean:

(7) OWM = (Y period 1) x (feed eaten period 1 x total feed eaten^{-1}) + (Y period 2) x (feed eaten period 2 x total feed eaten^{-1}) + (Y period 3 x (feed eaten period 3 x total feed eaten^{-1}),

where Y is FC_P, $FC_{P\ BW}$ or $FC_{P\ CW}$.

The direct feed cost calculations were initially conducted in Danish kroner (DKK) before being converted to US Dollars (USD) based on a DKK/USD exchange rate of 5.536, the average exchange rate in the 2012-2013 trial periods according to statistics from the National Bank of Denmark (http://nationalbanken.statistikbank.dk).

2.3.4 Feed cost including the value of faster salmon production cycle and increased sales value (opportunity cost)

This section provides the model that account for the opportunity cost of faster growth. This model builds upon equation 4 and 5 in the previous model. Thereafter, the difference in $FC_{P\ BW}$ including reduced production cycle is calculated:

(8) $FC_{P\ BW\ T}$ = (price kg^{-1} of LP feed x FCR_{BW} in the LP group) – (price kg^{-1} of HP feed x FCR_{BW} in the HP group) – $COST_{TIME}$ kg^{-1},

where $COST_{TIME}$ is subtracted from the better performing feeding strategy and computed as:

(9) $COST_{TIME}$ kg^{-1} = ((total operational cost – minus feed cost) x ($\sum T^{-1}$) in the LP feed strategy) - ((total operational cost – minus feed cost) x ($\sum T^{-1}$) in the HP feed strategy).

This is important as shorter production time increase the utilization of all fixed input factors. It is even more valuable when the regulatory system limit production capacity as in the Norwegian Maximum Total Biomass Regulations (MTB) (Asche et al., 2018b; Misund and Nygård, 2018).

The difference in $FC_{P\ BW\ T}$ including the sales value of higher harvest yield:

(10) $FC_{BW\ T\ SV}$ = (price kg^{-1} of LP feed x FCR_{BW} in the LP group) – (price kg^{-1} of HP feed x FCR_{BW} in the HP group) – $COST_{TIME}$ kg^{-1} + SV kg^{-1},

where SV kg^{-1} is the extra sales value of the harvested salmon of the better performing feeding strategy and computed as:

(11) SV kg^{-1} = (harvest weight of salmon x price kg^{-1} salmon in the LP group) – (harvest weight of salmon x price kg^{-1} salmon in the HP group)

Also here the alternative feed cost calculations were initially conducted in DKK before being converted to USD based on a DKK/USD exchange rate of 5.402, the average exchange rate in the 2009-2010 trial period (http://nationalbanken.statistikbank.dk). The inclusion of cost figures from the Norwegian industry as well as the salmon prices were based on an average NOK/USD exchange rate of 6.551 for the 2009-2016 period.

2.4 Price development

2.4.1 Feed ingredient prices

All raw materials display an increase in price from 2009 to 2016 (Fig. 2.). Except for a short period, in 2009, the marine ingredients fishmeal and fish oil have virtually been the most expensive protein and oil sources throughout the 2009 – 2016 period. Based on the gross energy content (MJ kg^{-1}), fishmeal and fish oil also display the highest relative price increase from 2009 to 2016. Fish oil has tripled the price from USD 0.018 kg MJ^{-1} to USD 0.06 kg MJ^{-1}, while fishmeal has had an increase of 63 %. This is important since the salmon production cost and price is highly influenced by the fishmeal and fish oil prices (Asche and Oglend, 2016; Misund et al., 2017). With regards to plant proteins, the energy derived from soy protein concentrate displays the highest increase in price (0.018 USD kg^{-1}), whereas wheat gluten and corn gluten, are the raw materials which display the lowest changes. The energy coming from rapeseed oil has had a 19 % price increase which is twelve times lower compared to price increase of fish oil in the same period.

2.4.2 Salmon prices

Salmon prices increased from 2009 to 2010 with a subsequent price decrease onwards to 2012. Thereafter, the price has increased since 2012 (Fig. 3). The three most commonly traded weight classes, 3-4 kg, 4-5 kg, and 5-6 kg, respectively, represent 75 % of the HOG salmon from 2009 to 2016 (Fig. 4). During this period, the Nasdaq index depicts that the price of HOG salmon generally increases with increasing weight classes. The relative increase is especially momentous in the smallest weight classes from 1-2 kg to 2-3 kg to 3-4 kg (Fig. 4.). Thus, by increasing the overall harvest weight within a given production cycle will not only lead to a greater tradeable biomass, but also an overall increase in value per kg salmon produced.

3. Results

3.1 Direct feed cost

3.1.1 Feed cost – Experiment 1 small-scale

Figure 5 depicts that the HP diets were higher priced compared to the LP diets throughout all feeding periods resulting in an overall higher weighted feed price (FC_P) for the HP feeding strategy (0.034 USD kg^{-1}). Because of better feed utilization and higher body weight gain, the calculations demonstrate a lower feed cost ($FC_{P\ BW}$) for the dietary HP group in the first (-0.007 USD kg^{-1}) and third (-0.001 USD kg^{-1}) period, whereas in the second period, the cost is higher, illustrating that there is a real trade-off between the two feed types. Overall, the $FC_{P\ BW}$ calculation demonstrated that the price difference of 0.034 USD kg^{-1} between the dietary strategies was reduced to 0.008 USD kg^{-1} when the difference in body weight gain was accounted for. When feed cost was based on carcass weight ($FC_{P\ CW}$) the HP strategy displayed a lower cost in the first (-0.035 USD kg^{-1}) and third (-0.058 USD kg^{-1}) period resulting in an overall lower feed cost (-0.039 USD kg^{-1}) for the whole experiment.

3.1.2 Feed cost – Experiment 2 small-scale

The HP feed was higher priced in all feeding periods (FC_P), resulting with an overall higher feed price of 0.111 USD kg^{-1} (Fig. 6). The HP strategy displayed a lower $FC_{P\ BW}$ in the autumn and spring periods and therefore decreasing the overall feed cost difference between the dietary strategies in these periods. However, the LP strategy demonstrated a lower $FC_{P\ BW}$ in the winter period, and therefore increasing the cost difference between the groups in the coldest period. Nevertheless, cold sea temperatures have a negative influence on feed intake in salmon and therefore the cost differences in the winter period had a relative low influence on the overall cost for the total period. Thus, the HP strategy displayed an overall lower $FC_{P\ BW}$ of 0.03 USD kg^{-1} compared to the LP feed strategy. Despite following the same pattern as the $FC_{P\ BW}$, the differences in $FC_{P\ CW}$ were even clearer because of higher carcass weight in the HP group. Overall, the HP feed strategy achieved a lower $FC_{P\ CW}$ of 0.07 USD kg^{-1}.

3.2 Feed cost including alternative cost

3.2.1 Feed cost – large-scale experiment

The overall weighted feed price for the HP dietary strategy was USD 0.162 kg^{-1} higher than the LP strategy (Fig. 7a). Because of better feed utilization in the HP group the feed cost difference ($FC_{P\ BW}$) was reduced to USD 0.102 kg^{-1}. Salmon in the dietary HP group had 219-day degrees (24 days) shorter production cycle than the LP group, which reduced the cost difference ($FC_{P\ BW\ T}$) down to USD 0.016 kg^{-1}. The final average harvest weight class was 3-4 kg, which was priced at USD 6.12 kg^{-1}. In addition to better feed utilization, the dietary HP group had 1.1 % higher harvest yield. This yield was equivalent to USD 0.065 kg^{-1} higher value of the produced biomass. Consequently, when the dietary induced production improvements were included in the overall feed cost evaluation ($FC_{P\ BW\ T\ SV}$), the HP strategy demonstrated an overall lower feed cost of USD 0.048 kg^{-1} (Fig. 7a).

Based on the data from 2009 to 2016 from the Norwegian salmon industry (Directorate of Fisheries, 2018), the feed prices increased with approximately 46 % in the period and the overall production cost excluding feed increased from USD 1.545 to 2.948 kg^{-1} (Table 5). In 2016, the average salmon prices for the 3-4 kg weight class was USD 9.10 kg^{-1} (Fig. 3). When repeating the same calculation with the biometric results from the large-scale feeding experiment with the actual salmon cost and salmon prices from 2016, the overall economic result was improved ($FC_{P\ BW\ T\ SV}$ = USD 0.076 kg^{-1}) despite even higher feed price difference (FC_P = USD 0.236 kg^{-1}) between the dietary HP and LP strategies (Fig. 7b).

4. Concluding remarks

From a cost perspective, feed is the most important input factor in salmon aquaculture. As aquafeed producers rapidly increased their share of the available fishmeal and fish oil in the 1990s, there were significant concerns with respect to the sustainability of the industry due to its dependence on marine ingredients in the feed (Naylor et al., 2000) and the competitiveness due to increased feed cost (Asche and Tveterås, 2004; Kristofersson and Anderson, 2004).

As one of the largest users of fishmeal and fish oil, salmon had been at the head of a development where improved nutritional knowledge reduced the share of marine ingredients in the feed (Ytrestøyl et al., 2015; Aas et al. 2018). The shift towards energy denser diets, especially in the grow out phase (> 1 kg) with less protein and more oil, has made it easier for the feed industry to use lower concentrated protein ingredients in the feed formulation for salmon. Until recently, literature has indicated that reducing the protein content and inverse increase of dietary oil has been achieved without sacrificing growth performance (Hillestad and Johnsen 1994: Hillestad et al., 1998; Azevedo et al., 2004, Karalazos et al., 2007; Karalazos et al., 2011). However, Weihe et al. (2018) nuance this conclusion by reporting improved feed conversion and faster growth with a high protein-to-lipid feeding strategy in full-scale trials, suggesting that the potential productivity increase caused by improved nutritional knowledge primarily has been taken out by providing cheaper feed, and not by improving growth performance. Hence, there is a trade-off between cheaper feed containing less protein and more expensive feed that improves growth performance. As feed prices varies significantly over time (Dahl and Oglend (2014) show that fishmeal is one of the most volatile commodities), this trade-off may also depend on the price levels of the different feed ingredients.

This trade-off is investigated in three experiments in this paper for two types of isoenergetic feed strategies: high and low protein-to-lipid ratio. The results indicate that there indeed is a trade-off as total cost per kg is lower in some periods with the commonly used low protein feed, while it is lowest in other periods with the high protein feed. When one accounts for the opportunity cost of secondary factors such as longer production time with the LP feed leading to poorer capacity utilization, the high protein feed performs even better, but it still does not dominate the lower protein feed. This suggest that a mixed strategy with respect to feeding might be preferable for any farm, given that sufficiently informative forecasts of salmon as well as fish feed prices can be obtained. This is relatively straightforward for the salmon price given the existence of a futures market (Asche et al., 2016b; Ankamah-Yeboah et al., 2017), with contracts fixing prices with buyers as an alternative (Misund and Nygård, 2018). For feed it is harder given that the price forecast must be made inhouse, but also here contracts (with the feed producers) are an alternative. Nevertheless, feed intake and growth performance in a given period might be a response to the condition of the salmon which has been influenced by previous feeding periods (Dessen et al., 2017; Rørvik et al., 2018). Although the choice of feed in a single period might be the most rationale economic choice, it may not be the best solution seen over a whole production cycle.

It is also worthwhile to note that the regulatory system in several of the salmon producing countries limit the biomass at each farm (Asche and Bjørndal, 2011). Such regulations will further increase the opportunity cost of the longer production process associated with low protein feeds, as it leads to poorer capacity utilization within the available biomass restriction. This adds to the opportunity cost of a longer production time. This effect becomes even stronger when the number of farms or licenses are also limited as in Norway, or when it in practice is hard or impossible to get new licenses like in Scotland, as production cannot be increased by adding more farms. A shorter production cycle will not increase any of the fixed costs, as e.g. smolt cost and harvesting cost is independent of the length of the production cycle. However, the extent to which the use of HP feed shortens the production cycle will increase total production it may improve capacity utilization for existing facilities reducing cost if there are any slack, and it may require additional investment in facilities like smolt production and harvesting plants if the production increase sufficiently. As long as the salmon industry remains profitable, the costs associated with these investments will be covered by the increased production.

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Figure captions

Fig. 1. Overview and duration of the three feeding experiments which form the basis of the biometrical data for the economic analysis of feed influenced fish performance. The two dietary strategies are depicted with thick black line (HP: high protein-to-lipid feeding strategy) and broken black line (LP: low protein-to-lipid feeding strategy), respectively. The number of experimental replicates per treatment per trial are denoted in brackets. The gray shaded areas represent the trial terminations, either as harvest (LS1 and SS2) or as restocking of HP fish group to another experiment (SS1).

Fig. 2. Price development in feed ingredients based on their gross energy content (MJ $kg^{-1)}$ from 2009 to 2016. FM: Fishmeal, WG: Wheat gluten, SPC: Soy-protein-concentrate, CG: Corn gluten, SFM: Sunflower meal, FO: Fish oil, RO: Rapseed oil (Sources: Chr. Holtermann ANS; Havsbrún; National Research Council, 2011).

Fig. 3. Annual prices of fresh head-on gutted (HOG) salmon from 2009 to 2016 divided into weight classes. Until week 13 in 2013, the 7+ weight class was the highest weight class which subsequently was divided into 7-8 kg, 8-9 kg, and 9+. Prices are originally given in NOK kg^{-1} (Norwegian currency) and converted to USD by the average NOK/USD exchange rate in the 2009-2016 period of 6.551 (Source: Fish Pool, 2018; National Bank of Norway, 2018).

Fig. 4. Distribution of fresh head-on gutted (HOG) salmon from 2009 to 2016. Until week 13 in 2013, the 7+ weight class was the highest weight class which subsequently was divided into 7-8 kg, 8-9 kg, and 9+ kg. The percentages represent the average increase in sales value of a given weight class when increased with 1 kg (Source: Fish Pool, 2018).

Fig. 5. Differences in direct feed cost development in post-smolt S1 salmon production from approximately 100 g to 950 g (small-scale experiment 1), using a dietary high protein-to-lipid feed strategy (HP) and a low protein-to-lipid feed strategy (LP). Negative and positive numbers represent a higher cost and lower cost, respectively, for the HP feed strategy. Difference in feed price (FC_P: white bars), difference in feed cost assessed after including the whole-body weight-based feed conversion ratio ($FC_{P\ BW}$: black bars), difference in feed cost assessed after including the carcass weight (head-on-gutted, HOG) based feed conversion ratio ($FC_{P\ CW}$: vertical striped bars), OWM: overall weighted mean.

Fig. 6. Differences in direct feed cost development in S1 salmon grow-out phase from approximately 1000 g to 3500 g, (small-scale experiment 2), using a dietary high protein-to-lipid feed strategy (HP) and a low protein-to-lipid feed strategy (LP). Negative and positive numbers represent a higher cost and lower cost, respectively, for the HP feed strategy. Difference in feed price (FC_P: white bars), difference in feed cost assessed after including the whole-body weight-based feed conversion ratio ($FC_{P\ BW}$: black bars), difference in feed cost assessed after including the carcass weight (head-on-gutted, HOG) based feed conversion ratio ($FC_{P\ CW}$: vertical striped bars), OWM: overall weighted mean.

Fig. 7. Development in feed cost differences in salmon production based on a dietary high protein-to-lipid feed strategy (HP) or dietary low protein-to-lipid feed strategy (LP), using the actual cost figures from the large-scale experiment in 2010 (A) as well as basing the same calculations with operational cost figures for 2016 (B). Negative and positive numbers represent a higher cost and lower cost, respectively, for the HP feed strategy. Difference in feed price (FC_{P}: white bars), difference in feed cost assessed after including the feed conversion process ($FC_{P\,BW}$: grey bars), difference in feed cost assessed after including the feed conversion process and production time ($FC_{P\,BW\,T}$: vertical stribed bars), difference in feed cost assessed after including the feed conversion process, production time and extra sales value of the salmon ($FC_{P\,BW\,T\,SV}$: horizontal striped bars).