



Modeling optimal dietary pigmentation strategies in farmed Atlantic salmon: Application of mixed-integer non-linear mathematical programming techniques

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Abstract

The most important visual quality characteristic of Atlantic salmon is the red/pink flesh color. The primary source of this coloration in salmon is caused by deposition of relatively large amounts of pigments, such as astaxanthin, obtained from their diet. Astaxanthin is expensive, and in commercial farming practice, dietary color pigments comprises about 15–20% of the total feed cost. One important operational process in commercial fish farms is therefore to minimize pigment costs. Based on recent models on the effects of dietary pigment concentration and fish size on visual color perception of Atlantic salmon, this study has built a mathematical programming model designed to optimize dietary astaxanthin concentrations throughout the grow-out period that results in well-pigmented fish at minimum cost. We have applied a mixed-integer non-linear programming algorithm to solve this problem. Various managerial implications of applying optimization models in product quality management of farmed salmon are discussed.

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1. Introduction

Farming of Atlantic salmon (*Salmo salar* L.) is an emerging global industry with an annual production of approximately 1,400,000 metric tons in year 2005, representing a market value of 6.0 billion USD or 4.9 billion Euros. About 85% of farmed salmon is produced in Norway, Chile and the UK, and fish are distributed into the global markets; each with different requirements regarding to fish quality. The most prominent visual

quality characteristic of salmonid fish including the Atlantic salmon is the red/pink flesh color. Consumer studies have consistently reported that muscle redness as one of the most important quality parameters for both raw and smoked salmon (Gormley, 1992; Sylvia et al., 1996; Kristoffersen, 1998). Borch and Aaker (1997) report a considerable variation in flesh color preference among different market segments. Generally, the Asian consumers markets and the “quality oriented” smoking industry prefer salmon with higher flesh redness than European consumer markets. As a consequence of different market preferences, appropriate flesh color is decisive for acceptance and price of salmon products (Alfnes et al., in press; Steine et al., 2005).

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The primary source of this coloration in salmon is caused by muscle deposition of relatively large amounts of carotenoids, such as astaxanthin, obtained from their diet (Torrissen et al., 1995). Astaxanthin is expensive, and in commercial farming practice, dietary color pigments comprises about 15–20% of the total feed cost, or 6–8% of total production costs (Torrissen, 1995). Since profit margins in salmon farming are in general low, just small changes in feed cost may change a salmon farm producing with deficit to a profitable one. One important operational process in commercial fish farms is therefore to balance the intensity of muscle color to the consumer demand at minimum cost.

Based on published literature data, Forsberg and Guttormsen (2006) modeled the effect on dietary pigment concentration and fish size on visual color perception of Atlantic salmon. Model outputs show that the red color intensity increases curve-linearly both with increasing dietary pigment concentrations and to increasing fish size. The aim of this study is to include the pigmentation model in a mathematical programming model designed to optimize dietary astaxanthin concentrations throughout the grow-out period that results in well-pigmented fish at minimum cost. This paper is structured into four parts. Firstly, a brief description of commercial salmon farming and feeding practice will be presented. A mathematical programming model will then be built to optimize dietary pigment concentrations. The model will be applied to solve different numerical examples. Finally, various managerial implications of optimization model in commercial salmon farms will be discussed.

2. Farm management and feeding practice

A Norwegian salmon farm with one licence¹ produces normally 700–1000 tons of fish per year. Young fish (smolts) at 50–200 g are produced in separate freshwater plants, and transferred to the seawater grow-out site between May and October every year. Different fish groups are kept in separate cages, and fed to satiation until they reach market size (3–8 kg). The on-growing production time will normally range between 12 and 24 months. Color pigments, such as astaxanthin, are supplied in the diet at varying concentrations, typically ranging from 20–70 mg astaxanthin/kg diet. In commercial salmon farming, dietary pigment concentrations normally change 2–4 times throughout the grow-out cycle. Generally, small fish are supplied higher doses of pigments than

larger fish. Further, higher doses of pigments supplied in feed will result in more intense red flesh color. The color pigments have no impact on growth rates.

Fish color can be measured by three methods: Chemically (pigment concentration, ppm), instrumentally (Minolta a^* , b^* , L values) and visually aided by color charts such as the *Roche Color Card for Salmonids* and the *SalmoFan* (Hoffmann-La Roche, Basel, Switzerland). Chemical and instrumental measurements are widely used by scientists due to its objective methods, which is not interfered by subjective impressions of the human eye. However, since visual assessments are the most common measure among fish farmers, fish feed producers, processing industry, marketing organizations and salmon buyers, we chose to use *SalmoFan* score as measure of fish pigmentation. *SalmoFan* is a further development of the *Roche Color Card*, and has today replaced the *Roche Color Card* as a globally accepted tool for evaluation and communication of salmonid flesh color. The *SalmoFan* score card range over 14 red colors with varying intensity of redness. Each of the colors are associated with a numerical value ranging from 20 (very pale red) to 34 (very intense red). In farmed Atlantic salmon fillets, *SalmoFan* score usually range between 23 and 29. A longitudinal variation in pigment content and red color is found, with more astaxanthin being deposited in the caudal (tail) than in the anterior (front) part (No and Storebakken, 1991). To standardize the sampling and measurement procedures, *SalmoFan* score is now measured in the flesh located posterior to the dorsal fin, which is also referred to as the *Norwegian Quality Cut*.

3. Model development

3.1. Pigment cost model

Divide the on-growing period from smolt transfer to harvest size into T time period. Let the vector $W=(W_1, W_2, \dots, W_T)$ be the fish sizes at time $t=1, 2, \dots, T$, where W_T is fish size (kg) at harvest. Estimates of W can be calculated from salmon growth models, such as Cho and Bureau (1998), and is here considered as an exogenous variable. Further, let the vector $Ad=(Ad_1, Ad_2, \dots, Ad_{T-1})$ be the dietary astaxanthin concentration (mg astaxanthin/kg diet) supplied to fish in period $(t, t+1)$. All elements in Ad are considered as decision variables set by the fish farmer.

The accumulated dietary pigment cost (NOK/kg fish) from smolt transfer to harvest sizes is simply:

$$C_T^{Asta} = C_1^{Asta} + C_2^{Asta} + \dots + C_T^{Asta} = \sum_{t=1}^T C_t^{Asta} \quad (1)$$

¹ To produce salmon in Norway, farmers need a license provided by the government. One license gives the owner the right to produce on 12 000 m³ water.

The pigment cost for a single time period ($t, t+1$) is the product of pigment concentration in diet and amount of feed supplied in the period:

$$C_t^{Asta} = c_A \text{Ad}_t \cdot (W_{t+1} - W_t) \cdot \text{FCR}_{W(t)} \quad \forall t \quad (2)$$

where c_A = astaxanthin unit cost (NOK/mg dietary astaxanthin) and $\text{FCR}_{W(t)}$ = size dependent feed conversion ratio (kg feed supplied/kg growth gained) for fish fed to satiation. The term $(W_{t+1} - W_t) \cdot \text{FCR}_{W(t)}$ is therefore an estimate of the amount of feed (kg) supplied to fish in the period. An analysis of present commercial feed tables given by the feed company EWOS (unpublished), it can be demonstrated that the instantaneous feed conversion ratio increases curve-linearly with increasing fish size:

$$\text{FCR}_{W(t)} = 0.94 \cdot W_t^{0.119} \quad (3)$$

By combining Eqs. ((1)–(3)), the accumulated dietary pigment costs can be expressed as:

$$C_T^{Asta} = 0.94 c_A \sum_{t=1}^{T-1} \text{Ad}_t \cdot (W_{t+1} - W_t) \cdot W_t^{0.119} \quad (4)$$

Generally, higher doses of pigments supplied in fed will result in more intense red flesh color. Let the vector $\text{SF} = (\text{SF}_1, \text{SF}_2, \dots, \text{SF}_T)$ be the *SalmoFan* score in fish muscle (Norwegian Quality Cut) resulting from the dietary pigment decisions represented by the Ad vector. Forsberg and Guttormsen (2006) show that each of the elements in SF can be estimated from the difference Eq. (5):

$$\text{SF}_t = \frac{1.49}{W_t} \left(W_1 \text{Af}_1 + \sum_{t=1}^{T-1} \frac{W_{t+1} \text{Af}_{t+1} - W_t \text{Af}_t}{W_{t+1} - W_t} \right) + 16.17 \quad \forall t \quad (5)$$

where Af_t = fish astaxanthin concentration (mg astaxanthin/kg fish) at time t estimated as (Forsberg and Guttormsen, 2006):

$$\text{Af}_t = 11.1 \cdot \exp^{-0.829/W_t} \frac{\text{Ad}_t}{11.9 + \text{Ad}_t} \quad (6)$$

Now, we have a complete set of equations that enables the fish farmer to estimate the *SalmoFan* score in fish muscle (Eq. (5)) and the resulting costs (Eq. (4)) by balancing the dietary astaxanthin decisions throughout the grow-out period. Note that model (5) and (6) is applicable for a fish stock, and calculates the average *SalmoFan* score value for the entire stock. This means that the model can calculate *real SalmoFan* score values (e.g. = 26.5) even that the *SalmoFan* score card consists to *integer* values (20, 21, 22, ..., 34).

3.2. Optimization of dietary pigment concentration

The fish farmer's optimization problem is to determine each element in the Ad vector that results in an acceptable muscle color in fish at minimum cost. This may be achieved by simulating different Ad scenarios, and choose the most cost efficient strategy among the scenarios that results in well-pigmented fish. However, due to the combinatorial complexity of this problem, the simulation approach is requires lots of computational time. As an example, if the fish farmer can choose among seven different dietary pigment levels in each of seven time periods throughout the production period, this gives a set of 823,543 possible combinations. An analysis speed of 100 scenarios per second would require 6 days of computational time to investigate all possible combinations. To reduce the computational time required to solve the problem, we have developed a non-linear programming model (NLP) which is well suited to solve non-linear combinatorial problems. NLP models have the general structure (Luenberger, 1989):

$$\begin{array}{ll} \text{Maximise (or minimise)} & f(x) \\ \text{Subjected to} & g(x) \leq B \\ & x \geq 0 \end{array}$$

The non-linear objective model $f(x)$ is a function of the decision variables $x = x_1, x_2, \dots, x_n$ subjected to a non-linear constraint function $g(x)$ which is not allowed to take values higher than the resource constraint B . The $x \geq 0$ assures that all $x \in x$ take positive values. Theory and applications of NLP can be found in operations research textbooks such as Luenberger (1989) and Winston (1991).

In practical feeding operations, the fish farmer cannot decide among an unlimited set of dietary pigment concentrations. Normally, the fish farmer have to choose between a pre-defined set of dietary pigment concentrations available by the feed manufacturer, usually 20, 30, 40, 50, 60 and 70 mg astaxanthin/kg diet. This problem can be solved as a mixed-integer non-linear mathematical programming problem:

$$\text{Objective } \min C_T^{Asta} = 0.94 c_A \sum_{t=1}^{T-1} \text{Ad}_t \cdot (W_{t+1} - W_t) \cdot W_t^{0.119} \quad (7)$$

$$\begin{aligned} \text{subjected to } \text{SF}_t = & \frac{1.49}{W_t} \left(W_1 f(\text{Ad}_1) \right. \\ & + \sum_{t=1}^{T-1} \frac{W_{t+1} f(\text{Ad}_{t+1}) - W_t f(\text{Ad}_t)}{W_{t+1} - W_t} \left. \right) \\ & + 16.17 \quad \forall t \end{aligned} \quad (8)$$

$$f(\text{Ad}_t) = 11.1 \cdot \exp^{-0.829/W_t} \frac{\text{Ad}_t}{11.9 + \text{Ad}_t} \quad \forall t \quad (9)$$

$$\text{SF}_t \geq \text{SF}_t^{\min} \quad \forall t \quad (10)$$

$$\text{Ad}_t = 10y_t \quad \forall t \quad (11)$$

$$y_t \geq 2 \quad \forall t \quad (12)$$

$$y_t \leq 7 \quad \forall t \quad (13)$$

y_t is an integer number for all t .

The NLP optimization algorithm determines the optimal combination of $\text{Ad} = \text{Ad}_1, \text{Ad}_2, \dots, \text{Ad}_7$ that minimizes the pigmentation cost (objective value; Eq. (7)) and allows none of the constraints to be violated. The constraints (8) and (9) couples the Ad decision to fish color model, which is identical to Eqs. (5) and (6), respectively. The binding constraint (10) ensures that the muscle color resulting from the Ad decisions will be equal or higher than these minimum requirements. The constraints (12)–(13) forces y_t to take one of the values $\{2, 3, 4, 5, 6, 7\}$ for all t . Constraint (11) ensures that all Ad_t takes one of the values $\{20, 30, 40, 50, 60, 70\}$ which is the normal range of dietary pigment concentrations available from the fish feed manufacturers. The mixed-integer non-linear optimization algorithm determines the optimal combination of $(y_1, y_2, \dots, y_7)$ that minimizes the pigmentation cost and allows none of the constraints to be violated.

4. Model examples

4.1. Model assumptions

The models were applied to explore the optimal pigmentation strategies at different product quality requirements (*SalmoFan* score values) for a size range of harvestable fish ($W_t = 4\text{--}6$ kg). The on-growing period was divided into six time periods (a–f), in which the fish have reached different sizes: a) 0.5–1.5 kg, b) 1.5–2.5 kg, c) 2.5–3.5 kg, d) 3.5–4.5 kg, e) 4.5–5.5 kg and f) 5.5–6.0 kg. In each of the periods, dietary astaxanthin concentration can range between 0 and 100 mg/kg diet. For the discrete-stepwise model, dietary pigment concentration can take one of the values $\{0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100\}$ mg/kg diet. The minimum *SalmoFan* score ($\text{SF}^{\min}$ vector) may represent different product quality requirements, and is set between 27 and 28 which is within the normal range of farmed Atlantic salmon. The astaxanthin unit cost was

set as $c_A = 20,000$ NOK/kg. The model was programmed in Microsoft Excel™ spreadsheet, and the optimisation problem was solved by the Excel Solver. The CPU time was < 10 s with a 2.8 GHz Pentium 4 processor.

4.2. Model results

Fig. 1 presents optimal pigmentation strategies given different product quality requirements. In Fig. 1A–C a *SalmoFan* score values of 27 was defined for different fish sizes A) 6 kg only, B) 5–6 kg, and C) 4–6 kg. Similar, in Fig. 1D–F *SalmoFan* score values was set as 28 to D) 6 kg only, E) 5–6 kg, and F) 4–6 kg. The model outputs show three general trends:

1. Smaller fish should be fed higher pigment concentrations than larger fish. In most cases, fish size of 0–2 kg are fed pigment concentrations 20–40 mg/kg higher than harvestable fish (4–6 kg).
2. The optimal dietary pigment concentration for a given fish size is 10–30 mg/kg higher in cases where *SalmoFan* score values was set to 28 (Fig. 1A–C) compared to the 27 cases (Fig. 1D–F). The increase in red color intensity (*SalmoFan* score values) in salmon muscle from 27 to 28, increased the pigment cost by 45–55%, or 0.30–0.40 NOK/kg.
3. The optimal pigmentation strategy is highly dependent on the definition of “harvest sized fish”. If fish farmer wants to harvest fish at 6 kg and is only interested to reach the desired *SalmoFan* score at this size, only one or two shifts in dietary pigment concentrations are required (Fig. 1A and D). If however the fish farmer wants that a larger size range of fish shall meet these product quality requirements, such as all fish between 5–6 kg (Fig. 1B and E) or 4–6 kg (Fig. 1C and F), fish farmer should shift dietary pigment concentration more frequent.

5. Discussion

A variety of methods and techniques have been applied to optimize harvest outputs from fish farms. These are different analytical solved bio-economic models (Bjørndal, 1988; Hean, 1994), multi-period linear programming models (Forsberg, 1996; Forsberg, 1999), optimal control theory (Cacho et al., 1991; Arnasson, 1992; Heaps, 1993) and dynamic programming models (Leung et al., 1990; Cacho, 1997). These studies have basically been tailored the problem of optimizing fish growth and long-term stocking and harvest planning, taking into account simultaneously optimal use of feed, water and other limited resources, as well as long-term sales price forecasts and

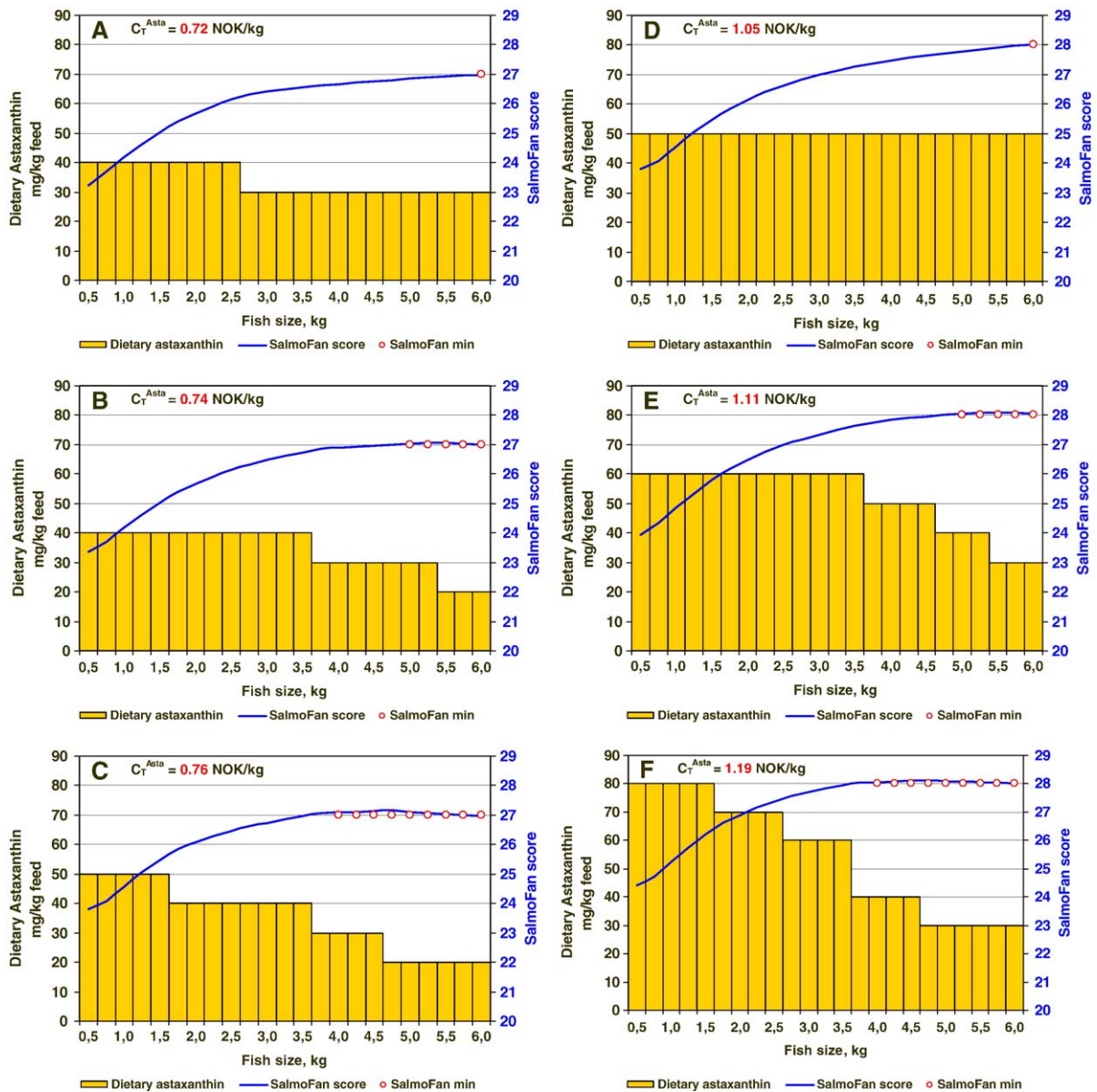


Fig. 1. Optimal dietary pigment strategies (bars) for farmed Atlantic salmon and the resulting *SalmoFan* score (line) given six cases (A–F) with different minimum *SalmoFan* score constraints (open dots). *SalmoFan* requirements are defined as 27 (A–C) and 28 (D–F) set for different fish sizes. C_T^{Asta} is accumulated pigment costs throughout the on-growing period.

market demand. None of them have explicitly included fish quality as decision criteria, such as visual skin quality, flesh color and muscle fat content. This paper is therefore the first study on optimization of fish product quality solved by mathematical programming techniques.

Market and consumer studies have consistently demonstrated that visual perception of muscle color is one of the most important quality traits in farmed salmon (Gormley, 1992; Sylvia et al., 1996). There is also reported considerable variation in flesh color preference among

different market segments (Borch and Aaker, 1997), but also among salmon buyers within the same segment (Alfnes et al., in press; Kristoffersen, 1998). The optimization model presented in this paper, has explicitly linked different consumer preferences through the definition of the $SF^{\min}$ vector (Eq. (10)), *SalmoFan* score values can therefore reflect muscle color requirements of varying fish sizes. The optimization model can therefore allow fish farmers to tailor the pigmentation strategies more specifically to different consumer requirements. Such

differentiation would be more cost efficient compared to the “one strategy fits all consumers” which is a common thinking among most farm managers.

The model results show that the optimal dietary pigmentation strategy is very sensitive to the definition of harvest size. Initially, the fish farmer may plan to harvest the fish at large size (e.g. 6 kg) with *SalmoFan* score=28. In this case, an optimal pigmentation strategy would be to supply 50 mg astaxanthin/kg diet constantly over the grow-out period, from smolt transfer to harvest size (Fig. 1D). Throughout the 1–2 year grow-out period, however, a variety of biological or market conditions can change, which may force fish farmers to harvest fish at smaller size (e.g. 4 kg). With the initial pigmentation strategy of 50 mg/kg diet for all fish sizes, a fish stock with average size of 4 kg fish will not meet market requirements of $SF^{\min}=28$, but only 27.5. In order to reduce market risks of badly pigmented fish, it may be wise to ensure that harvestable fish at any size are well pigmented, even that this may increase pigment costs. The study of risk elements in optimal product quality management would be topics for future studies.

Due to biological differences in feed intake and astaxanthin metabolism among individual fish, there are reported a considerable individual variation in fish color in salmon. Analysis of the data from Christiansen et al. (1995) show that individual fish with flesh astaxanthin concentration of 7 mg/kg, can range over a *Roche Color Card* score between 13–16, which corresponds to a *SalmoFan* score between 23–29 (mean $\pm$ SD $\approx 26 \pm 1$). This red color variation may have an impact in the profit margins from the harvested fish. Results from an experimental market study based on Norwegian salmon consumers, indicated that consumers are willing to pay a relatively high premium for increasing flesh redness, from *SalmoFan* score=21 up to 25 (Alfnes et al., in press; Steine et al., 2005). For salmon color above 25, the willingness to pay (WTP) is marginal. These findings might lead fish farmers to believe that the optimum *SalmoFan* score for harvested fish is 25. However this is correct only for an individual fish. Due to individual color variations in a harvest stock, a group mean $\pm$ SD *SalmoFan* score of 25 ± 1 , would result in *SalmoFan* score values of 24 and lower for about 30% of the individual fish. This pale-colored fish many not only result in lower profits, but can also lead to consumer complaints and may concern the producer–consumer relationship negatively. To ensure that 95% of the individual fish have acceptable muscle color (score values ≥ 25), the average *SalmoFan* score for the harvest stock should be 26.6. More information about individual color variation within a fish group and market studies of WTP in different salmon market segments would make us able to build a profit

function for salmon color. The cost-minimization model could then be replaced with a more robust profit-maximization model, which may be a better tool for designing optimal pigmentation strategies for farmed salmon.

In this study, the color pigmentation model (Eq. (6)) is drawn from analyses of the small-scale, controlled experiments (Forsberg and Guttormsen, 2006), which may not fully represent conditions in commercial grow out farms. Studies have shown that there are other than fish size and dietary pigment concentration that may determine the astaxanthin deposition and visual color in fish flesh. Among these are dietary fat (Einen and Roem, 1997; Hamre et al., 2004), genetic origin (Rye and Gjerde, 1996; Gjedrem, 2000), stress level prior to slaughtering (Robb et al., 2000; Sigholt et al., 1997) and temperature after slaughtering (Torrisen et al., 1999). There is also evidence that time of seawater transfer (0+, 1+ smolts) and seasonality may have an impact on salmon flesh color (Mørkøre and Rørvik, 2001). The pigment optimisation models should therefore be used with caution. In commercial fish farming, the pigmentation model (Eqs. (6) and (9)) and should be tested, and possibly be replaced by a more valid model incorporating more explanatory variables than dietary pigment concentration and fish size. Such relationship can be performed by multivariate statistical analysis of commercial farming data. When more accurate pigmentation models emerges in the future, these can then replace Eq. (8) and Eq. (9) in the optimisation model. Eq. (8) will be changed if new structural relationships between muscle pigments and the explanatory variables are found (dietary astaxanthin, fish size, smolt transfer, season, dietary condition etc.). Eq. (9) will be changed if the relationship between chemical pigment concentration and *SalmoFan* score values are identifies. Extending the optimisation model to be more applicable to commercial salmon farming will therefore be subjects for future studies.

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