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Feasibility of High Omega-3 Soybean Oil for Deep-Water Mariculture Diets

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Abstract

The growth of global aquaculture has put intense pressure on sources of fish oil and fishmeal for aquafeeds. GM soybeans could provide substitutes in high Omega-3 soybean oil (STA oil), as well as soy protein concentrate (SPC). This paper examines the technological and economic feasibility of substituting STA oil for one-half the fish oil in the diet of S. rivoliana. We find that the two feed technologies are essentially identical, with respect to growth pattern, feed consumption, and flesh quality. Economic feasibility depends upon the price of STA oil being lower than the price of fish oil. We estimate that it will be when it becomes available. The estimated production cost savings is small (about 1%). However, the potential global market for STA oil could be as much as 250 thousand metric tons annually; which would require soybean production equivalent to that from 1.6% of current U.S. soybean area.

Keywords: Omega-3 soybean oil (STA oil), aquaculture, asset replacement principles, diets/rations.

JEL codes: O13, O33

1. Introduction

Global aquaculture production (inland and marine) doubled between 2000 and 2012 (FAO Fisheries and Aquaculture Department, 2014), while production of compounded aquaculture feed from the feed industry increased about five fold (Alltech 2013, Tacon 1997). Because fishmeal and fish oil are primary components in aquafeed, the rapid growth of aquaculture is putting pressure on the fisheries that provide these components, and increasing fish oil prices relative to high Omega-3 soybean oil prices (Figures 1-2).

Previous experiments have shown that soy protein concentrate (SPC) can successfully replace fishmeal in the diets of aquaculture[1]. Recent experiments with genetically engineered/modified (GM) soybean oil rich in Omega-3 fatty acids, or STA oil, (Eckert, *et al*. 2006) demonstrate that this new oil source can successfully replace up to 50% of fish oil in these diets (Clemente 2011 and 2013)[2]. This substitution would result in increased demand for soybeans and reduced pressure on anchovy and other fisheries that currently provide fish oil. In this study, I examine the feasibility and potential implications of the inclusion of STA oil into the diets of the *S. rivoliana* species (a species of amberjack with various common names including longfin yellowtail).

Economic evaluation of the feasibility and implications of substituting STA oil for fish oil requires an evaluation of optimal fish harvest age, since the experiments suggest that the consumption and growth rates may differ under the two diets. Here I utilize experimental data to examine optimal harvest ages and economic performance using the two diets.

The organization of this paper is as follows. Following the introduction, Section 2 describes the data and methods used to find the optimal age to harvest *S. rivoliana* under the two rations. In Section 3, I estimate cost and returns at optimal harvest ages for the two technologies, along with an additional scenario. Section 4 reports the potential

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[1] Hamlet Protein 1995 and 1997; Kaushik *et al.* 1995; Refstie *et al.* 1998; Mambrini *et al.* 1999; Forster *et al.* 2002; Cremer *et al.* 2006; Caditec Testing S.L. 2007 and 2008; Davis, undated; Cremer *et al.* 2007 and 2008; Lan *et al.* 2007; Hart and Brown, undated; Drawbridge *et al.* 2008a, 2008b; Sookying and Davis 2011.

[2] The consumer panel taste test by the Food Innovation Center of Oregon State University showed that consumers could not tell a difference between the fish fed the STA oil vs traditional diets.

implications of adoption of the STA oil-based technology, while the final section reports a summary and conclusions.

2. Data and Methods

2.1. Experimental Data

Data from six experimental trials are used to predict body weight and cumulative feed consumed by *S. rivoliana* when fed STA oil versus traditional rations. Kampachi Farms, a Hawaii-based mariculture company, and the University of Nebraska Lincoln (UNL) jointly conducted the experimental trials. Five of the trials were conducted in tanks, one in deep-sea cages. Commercial production of this and similar fish species occurs predominantly in deep ocean facilities (mariculture). These trials were conducted in different years (2005 to 2013) as well as over different lengths of time (50 to 330 days) (Table 1).

__Insert Table 1 here__

Experimental treatments consist of the following rations: (i) one of two traditional rations based on fish oil (Commercial A or Commercial B[3]), and (ii) a STA oil ration in which 50% of the fish oil is replaced by STA oil. The remaining ingredients in the STA oil diets were formulated to match to the commercial rations. The detailed compositions of feed ingredients are reported in Table 2. Descriptive statistics of the experimental results are reported in Table 1. The analysis of feed to gain ratios in the different stages of life cycle of fish show mixed results, in some cases feed to gain ration is much better for STA oil diet than traditional diet and in some cases other way around. I pooled all the data, with indicator variables for ration and location, for a statistical analysis of growth and feed consumption, and used these results to estimate cost and benefits of STA oil to replace fish oil.

2.1.1. Feed Ingredient Prices

The economic feasibility of substituting STA oil for fish oil will depend on price as well as fish performance. I use 2013 prices for this analysis (Table 2). Because there is no STA oil on the market, I estimate its price to be $1.478 per metric ton (mt) considering

[3] Commercial feeds supplied by two large animal and aquatic feed suppliers.

the additional costs of segregation and identity preservation at scale would increase the cost by about 40% above that for commodity soybean oil. Perrin and Fulginiti (2011) reported that the price of STA oil would be about 22-40% higher than regular soybean oil because of the additional production and processing costs of identity preservation and segregation (IPS) that would be required for GM high Omega-3 soybean oil.

The price of fish oil in 2013 ($2042/mt) was almost double that of regular soybean oil. Recent relative prices of fish oil and STA oil (so calculated) indicate the relative price of fish oil to STA oil would have been above 1.0 since May 2012, with a ratio of 1.38 in 2013, and 1.47 in 2014 (Figure 1).

__Insert Figure 1 and 2 here__

In the absence of a reliable 2013 price for SPC, I estimate it as 4.7 times the price of soybean meal (the average ratio of SPC to soybean meal price from five reports of SPC price between 2000 and 2009[4]). The resulting estimate in 2013 prices is $2555/metric ton (mt), which is about 46% higher than 2013 fishmeal price ($1747/ mt) (World Bank 2014).

Table 2 lists the inclusion levels of ingredients and their cost to produce one kg of ration, using 2013 ingredient prices. The estimated market price of the STA oil aquafeed (after adding processors' gross margin) is $2.794/kg versus $2.855/kg for the traditional ration; about 2.14% lower than the traditional ration.

__Insert Table 2 here__

2.2 Methods

2.2.1. Fish Growth and Consumption Functions

To determine the profit-maximizing harvest age with STA oil rations, I must estimate feed consumption and fish growth through time. The general relationship for predictors of consumption and growth can be written as:

$$y_{it} = E(y_{it}|x_{it}) = f\left(x_{it}, \theta_j\right) \qquad (1),$$

[4] Hardy (2000), Forster, *et al.* (2002), Schmalz (2007), Griffis (2008), and Weingartner and Owen (2009)

where, y_{it} is the weight or consumption for treatment *i* at time *t*; x_{it} is a vector of predictor variables; f is a function of p parameters, $\theta_1, \ldots \ldots, \theta_p$.

Many possible specifications of the function, *f*, have been used to predict animal growth. To study fish growth, the von Bertalanffy model has been adopted *a priori* by many researchers; however, as reported by Katsanevakis and Maravelias (2008), in many cases fish growth data do not support it. They fit four candidate functions (Bertalanffy, Gompertz, logistic, and power) to 133 sets of length-at-age data. The "best" model was then selected by minimizing the small-sample, bias-corrected form of the Akaike information criterion (AICc). They found that for only 34.6% of the sets was the Bertalanffy the best model. In this study, I compared the goodness of fit for three models (Bertalanffy, logistic, and Gompertz) and found the Gompertz model to provide the best fit, which is selected for fitting the growth of *S. rivoliana.*

Substituting the Gompertz function into equation 1, I specify the growth regression as:

$$w_{it} = \alpha \exp\left(-exp\left(-\kappa(a_{it} - \tau)\right)\right) + \varepsilon_{it} \qquad (2),$$

where, w_{it} is the weight per fish with treatment i, *t* is the time elapsed since the beginning of the trial, a_{it} is the age of the fish, α is the upper asymptote, κ is the rate of change in growth of fish, τ is the inflection point, and ε_{it} is random error assumed to be identically and independently distributed. To obtain the nonlinear least squares estimates, starting values for parameters are required. There are many methods that can be applied to find the starting values for fitting nonlinear models (Bates and Watts 1988). I use both educated guess and the linearized transformation methods to find starting values and find the parameter estimates to converge to the same estimates.

To fit a feed consumption path from cumulative feed intake data, I use the power function:

$$F = \gamma_1 a^{\gamma_2} + \varepsilon \qquad (3),$$

where *F* is cumulative feed intake through age a, $\gamma_1$is the intercept, γ_2 expresses the rate of increase in feed intake, and ε is a random term.

2.2.2. Optimal Harvest Age Using the Asset Replacement Principle

Continuous-time optimization

I use the asset replacement principles derived by Perrin (1972) to estimate the optimal age to harvest fish. The criterion is to choose a harvest age, s, that maximizes the present value of earnings from the current and all future generations when harvested at age s. The corresponding first-order condition is the marginal principle "*to compare gains from keeping the current asset for another time interval with the opportunity gains that could be realized from a replacement asset during the same interval*" (Perrin 1972).

This marginal condition for the optimal replacement age (s^*) can be expressed as (Perrin 1972, equation 2):

$$R(s^*) + M'(s^*) = \rho M(s^*) \ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

Where, $R(s)$ is the flow of revenue (negative flow, reflecting costs in our case) associated with the asset at age s, $M(s)$ is market value at age s, $M'(s)$ is the change in market value of the asset at age s. $M(s)$ multiplied by the interest rate, ρ, represents the opportunity cost of holding the asset for one more unit of time. This marginal condition determines the optimal replacement age, s^*.

In our case, $M(s) = w(s) * p$, where w is the weight of a fish at age s and p is the price per unit weight of the fish. $R(s) = -k * \frac{dF}{ds}$, is the feed cost to raise a fish through age s, where k is price per unit of feed. Replacing $M(s)$ and $R(s)$ with the Gompertz function and power function, respectively, the marginal condition for optimal harvest age s becomes:

$$-k\gamma_1\gamma_2 s^{(\gamma_2-1)} + p\alpha\kappa\, e^{\left(-e^{(-\kappa(s-\tau))}\right)} e^{(-\kappa(s-\tau))} = p\rho\alpha\, e^{\left(-e^{(-\kappa(s-\tau))}\right)} \qquad (5),$$

where, k and p, respectively, are the price of feed ($/kg) and price of fish ($/kg); other parameters are as defined before. I obtain s^* numerically, by successive iteration on values of s to obtain the value that solves equation 5.

Discrete-time optimization

For the discrete case the marginal condition (equation 4) changes in two ways. The equality sign changes to greater than or equal to, ensuring that the fish is held for another interval only if the returns from that interval are greater than the opportunity cost of starting the next fish. Second the right hand side is replaced with $\frac{r}{1-(1+r)^{-s}}V(s)$ (equation 4.2, Perrin 1972), where V(s) is the present value of an upcoming replacement cycle given the replacement age s. The first term is the capital recovery factor $(c.r.f)$ that converts the present value V(s), into an annuity of equal periodic (daily) payments during interval s.

3. Results

3.1. Annualized Returns: Discrete Case

Tables 3 and 4 present the results of the discrete-time fish harvest problem with STA oil and traditional rations for the discrete choice set consisting of the ages at which fish were actually weighted in the 2011 trial[5]. For the STA oil diet, simple net return for a single harvest cycle would be maximized at $15.52 per fish by harvesting at 261 days ($0.059/day). However, that would delay the beginning of the next cycle of fish in the production facility, which represents the opportunity cost of delaying harvest. Simple net return per year (or per day) per unit of capacity is maximized at 196 days, yielding $23.62 per year ($.065 per day). Now adding consideration of the time value of money at the 10% annual rate, the choice of 196 days for harvest age does not change in this case, but the annual return per unit of capacity falls somewhat to $22.82 per year, equivalent to an interest-rate-adjusted daily annuity of $0.063 per day.

For the traditional diet, the optimal harvest age similarly calculated is 261 days. This results in an annualized return of $14.78 per unit of capacity, equivalent to an interest-rate-adjusted daily annuity of $0.040 per day, just 65% of that for fish fed on the STA oil

[5] Even though I exclude the data points in 2011 Traditional-A from 128 days onward in the analysis of continuous annualized returns due to the unequal numbers of fish were in the tank, I used these data in the discrete case because this is the only trial that has the longest grow-out period.

diet. The true optimal harvest age for these fish may be later than 261 days, with a higher annualized return, but no observations are available for later ages.

__Insert Tables 3 and 4 here__

3.2. Annualized Returns: Continuous Case

3.2.1 Fitted Growth and Consumption Functions

To allow for different growth and consumption paths for the two diets, I introduce an indicator variable D_1, equal to 1 for the traditional ration, 0 for the STA oil. I introduce another indicator variable, D_2 for location, equal to 1 for the offshore trials, 0 for tank trials. I use R to estimate this modification of equation (2).

$$w_{it} = (\alpha_{11} + \alpha_{12}D_1 + \alpha_{13}D_2)\, e^{\left(-e^{\left(-(\kappa_{11}+\kappa_{12}D_1+\kappa_{13}D_2)(s-(\tau_{11}+\tau_{12}D_1+\tau_{13}D_2))\right)}\right)} \qquad (6),$$

where, the relevant coefficients for growth using STA oil feed are α_{11}, κ_{11} and τ_{11}, while corresponding coefficients for growth using traditional feed are $\alpha_{11} + \alpha_{12}, \kappa_{11} + \kappa_{12}$ and $\tau_{11} + \tau_{12}$; the coefficients for offshore would be $\alpha_{11} + \alpha_{13}, \kappa_{11} + \kappa_{13}$ and $\tau_{11} + \tau_{13}$, which are not of our interest. The parameters estimates (not reported) show that there is no significant difference in the change in growth rates and inflection points between the STA oil vs traditional ration. I also conducted the extra sum of squares *F* test to find whether or not there is any difference between the two rations and in the parameters between the two treatments. I find that they are not significantly different from zero at the 5% level, indicating that the growth rates do not differ under the two rations. I conclude that the growth paths for STA oil and rational ration are virtually indistinguishable.

The estimated asymptote for STA oil and traditional are 1.865 kg and 2.256 kg, respectively, whereas the true asymptote must be bigger as yellowtails reportedly grow up to 50-60 kg[6]. The estimate of asymptote for offshore was 3.372 kg. I estimate the following specification assuming a common asymptote, $\alpha_{11} = \alpha_{12} = \alpha_{13} = 3.372$ along with the assumption $\kappa_{11} = \kappa_{12}$, and $\tau_{11} = \tau_{12}$.

$$w_{it} = 3.372 * e^{\left(-e^{\left(-(\kappa_{11}+\kappa_{13}D_2)(s-(\tau_{11}+\tau_{13}D_2))\right)}\right)} \qquad (7).$$

[6] *S. rivoliana* species grow up to 60kg (http://www.fishbase.org/summary/1007).

Estimated coefficients and statistical details are shown in Table 5.

__Insert Table 5 here__

I modify equation 3, again using the indicator variables D_1 and D_2, to estimate the path of feed consumption:

$$F_{it} = (\gamma_{11} + \gamma_{12}D_1 + \gamma_{13}D_2)a_{it}^{(\gamma_{21}+\gamma_{22}D_1+\gamma_{23}D_2)} \qquad (8).$$

Estimated coefficients (not reported) show that intercept and growth rates for the two rations are not significantly different. Using the extra-sum of square *F* test I again infer that the changes in rates of feed intake and intercepts are not significantly different at the 5% level. In other words, like a common growth curve a common feed consumption curve can be fit for STA oil and traditional rations.

$$F_{it} = (\gamma_{11} + \gamma_{13}D_2)a_{it}^{(\gamma_{21}+\gamma_{23}D_2)} \qquad (9).$$

I use the coefficients (Table 6) estimated from equation 9 to fit a common consumption curve for STA oil and traditional ration (Figure 3). The estimated feed conversion rate at a harvest weight of 2.25 kg is 1.546. For comparison, the feed conversions for Japanese yellowtail (a *Seriola* species) fed pelleted feeds in studies from 1993 to 2010[7] suggest that FCRs vary considerably (1.1 to 4.8) because of feed types, feeding practices (Miranda and Peet 2008), and harvest time chosen.

__Insert Table 6 here__

__Insert Figure 3 here__

3.2.2. Economic Implications

Table 7 compares optimal management results under the two rations with two possible scenarios. I substitute the estimated coefficients from equations 7 and 9 into equation 5 to solve for the optimal harvest ages (model 1). The optimal harvest ages are the same for both the STA oil and traditional rations (221 vs 220 days); the optimal body weights are 1.65 kg and 1.64 kg per fish, respectively. The previous studies of the *Seriola* species

[7] Watanabe *et al.* 1993, Nakada 2000, Benetti *et al.* 2005, Kofuji et al. 2006, Moran *et al*. 2010.

grown in aquacultures around the world (Table 8) suggest that fish can even be harvested at the weight of 1 kg. However, *S. rivoliana* for the sushi market is actually harvested at the weight of 2.25 kg because of consumers' preferences[8]. As we have data only for a portion of the life cycle of *S. rivoliana*, the estimated asymptote from data (small relative to what it could be) affects the estimated optimal weight. To approximate the results of commercial productions, I therefore calculate the age consistent with a 2.25 kg body weight using the estimated coefficients of model 2.

The estimated ages (model 2) that are necessary for 2.25 kg are 292 days for both the STA oil and the traditional ration. The estimated feed to gain ratio (FCR) is 1.546 for both rations, however, the feed cost per kg of fish produced is 2.2% cheaper for STA oil diet as the STA oil is cheaper than the fish oil. Given our estimate of ration prices ($2.794/kg for STA oil, $2.855/kg for traditional) and fish prices ($13.0/kg[9]) the estimated return over feed cost for the STA oil diet is $8.68 per kg of fish, higher than the $8.59 per kg of fish returns under the commercial diet. Undiscounted net return over feed cost per day per fish harvested is $0.030 with the STA oil ration, $0.029 with the traditional ration, both numbers slightly less on an annualized basis. Therefore, the adoption of STA oil for aquafeed is economically feasible, increasing returns over feed cost by about 1.1% at 2013 prices.

__Insert Tables 7 and 8 here__

Feed costs represent about one third of the market value of these fish. In Table 9 I report the estimate of total production costs per metric ton of fish using the two rations. I assume that all costs other than feed are fixed with respect to the choice of ration. Feed costs here are calculated using feed conversion ratios from Table 7. I estimate fingerling/juvenile costs to be $2.0 per kg of fish produced[10]. Kamstra (2013) provides an

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[8] Personal communication, Neil Sims of Kampachi Farms

[9] Our estimate of $13 is the price of fish in tank, based on an industry source. Market price of per kg yellowtail kingfish is about 14 Euro ($17.5) (Kamstra 2013). Nakada (2008) reported that the price of 600gm of amberjack is $14.3. Hawaiian yellowtail fillets are sold in small quantities (Dec, 2014) for $8.75/lb delivered, http://cookingfortwo.about.com/od/reviewsrecommendations/fr/yellowtail.htm. Price of fresh-gutted salmon is lower than these prices.

[10] Kamstra projected juvenile cost of $1.84 per kg of yellowtail Kingfish produced. Nakada (2008) reported the price of one 50gm weight amberjack juvenile to be $4.8. I divide $4.8 by the optimal body-weight to

estimate of labor cost at about $1.50 per kg of fish. Helsley (1999) estimated labor cost to be about $3.33[11] per kg of fish produced, based on a demonstration project on cage culture of *Polydactylus sexfilis*, I use the average as the estimate of labor cost, $2.42 per kg of fish produced. Other capital, management and transportation costs I estimate by subtracting all costs from the market price of fish, as it is assumed that all revenue is paid to factors.

The estimates above indicate that the STA oil ration is a cost saving technology, reducing feed costs by 2.2% and total cost by about 1.0% (Table 9).

__Insert Table 9 here__

3.2.3 Implications of Aqua-industry Adoption of STA oil diets

This study was conducted for *S. rivoliana*, a minor aquaculture-produced species, but the results are likely to be similar for closely related species and even for farmed Atlantic salmon. I estimate the potential aquaculture market for STA oil by considering each of these species; potential aquaculture demand for STA oil are presented in Table 10. Based on current global aquaculture production of various *Seriola* species alone, potential STA oil demand is about 39,000 metric tons per year, which could be supplied by about 191,000 acres of GM soybeans. Adding to this the potential feed requirements of farmed Atlantic salmon raises the total potential demand to just over 252,000 metric tons, which would require production from approximately 1.24 million acres of soybeans (about 1.6% of current U.S. soybean acreage).

__Insert Table 10 here__

get juvenile cost per kg of fish produced ($4.8/2.25=$2.13). Taking average of these two numbers I obtain our estimate of fingerling cost per kg of fish produced (i.e. $2.0 for traditional ration).

[11] There were 70,000 fingerlings were stocked in 3000 cages. They harvested 52,000 fish equivalent to 18,000 kg after 180 days. The labor cost during the six month was estimated $60,000. Labor cost would be $3.33 per kg fish produced (=$60,000/18000).

4. Conclusion

This research investigates the economic feasibility and potential impact of substituting high omega-3 soybean oil (STA oil) for one-half the fish oil in an aquaculture diet. Analysis reveals that the two feed technologies are essentially identical with respect to growth pattern, feed consumption, and flesh quality. Economic feasibility depends then upon the price of STA oil being lower than the price of fish oil. There is not yet any STA oil in the market, but we estimate that the additional costs of segregation and identity preservation at scale would increase the cost by about 40% above that for commodity soybean oil. At 2013 prices, this would imply a market price of $1478/mt for STA oil, versus $2042/mt for fish oil, so the substitution is would be economically feasible. Fish oil represents only 12% of the ration cost, and only half of that would be replaced with slightly cheaper feed, so the total production cost savings are small (about 1%). It is evident that the price of fish oil relative to commodity soybean oil is rising, so the advantage of STA oil should be rising as well.

I conclude that the inclusion of high Omega-3 soybean oil (STA oil) into diets for *S. rivoliana* is both technically and economically feasible under current and prospective price regimes. In addition, the reliance upon soybeans rather than anchovy fisheries for oil feed could improve the sustainability of mariculture production. The adoption of this technology would add to soybean demand in the future. The potential global market for STA oil may be as high as 252,000 metric tons annually, which would require about 1.24 million acres of GM soybeans high in Omega-3 oils, equivalent to 1.6% of U.S. soybean area. The U.S. soybean farmers and processors, and mariculture firms have the potential to gain from this technology, while Peruvian anchovy fishermen and fishmeal/fish oil processors have the potential to lose and the aquaculture industry would be based on more sustainable footing. Estimates of the sizes of these welfare gains and loses remain to be explored.

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Lists of Tables

Table 1: Descriptive statistics of experiments used in this study

Year and type	Treatment[a]	Length of experiment (days)	Feed to weight gain ratio					
			15-99 days	99-128 days	128-168 days	168-196 days	196-261 days	Average
2005-2009, offshore	Traditional A	330	1.47	1.68	1.87	2.12	2.18	1.91
2010, tank	STA oil	92	1.05					1.05
	Traditional A		1.01					1.01
2011, tank	STA oil	240	0.93	1.14	1.40	1.44	2.20	1.42
	Traditional A		0.94	1.21	1.26	1.38	1.54	1.31
2012a, tank	STA oil	79	0.97					0.97
	Traditional B	261	0.98	1.80	1.78	1.95	1.38	1.56
2012b, tank	STA oil	50			1.77			1.77
	Traditional B				1.62			1.62
2013, tank	STA oil	77			1.46	2.01		1.69
	Traditional B				1.54	1.76		1.64

Source: UNL-Kampachi experiments, 2005-2013.

Notes: Both diets use 40% SPC (soy protein concentrate). The STA oil diet substitutes the Omega-3 soybean oil (STA oil) for half of the fish oil of traditional diets. In offshore experiment, last two data points for feed consumption are missing; so feed conversion is estimated at the point where weight gain was 2028 gm. I exclude the data points in 2011 Traditional-A from 128 days onward in the analysis of continuous annualized returns because the number of fish in the tank were not equal under the STA oil vs traditional rations. The 2012a STA oil experiment was stopped at 93 days, while 2012a Traditional B was continued up to 275 days.

Table 2: Components and costs ($/kg) of STA oil and traditional rations

Ingredients	Price of ingredients ($/Kg)	Traditional ration		STA oil ration	
		Quantity (%)	Cost ($/Kg) of ration	Quantity (%)	Cost ($/Kg) of ration[b]
Procon 2000 (SPC) 68.9/0.8	2.555	40.000	1.022	40.000	1.022
Fishmeal, Anchovy 71.6/7.8	1.747	11.890	0.208	11.890	0.208
Fishoil	2.042	17.300	0.353	8.650	0.177
Omega-3 Soybean oil/STA oil	1.480		0.000	8.650	0.128
Others		30.810	0.766	30.810	0.763
Potato Starch	3.409	7.420	0.253	8.020	0.273
Fish, HFPC 74.6/8	1.750	3.440	0.060	3.440	0.060
Squid Meal 85.2/3.6	2.250	4.400	0.099	4.400	0.099
Blood Meal SD 92/0.3	1.800	6.070	0.109	6.070	0.109
Taurine	2.800	4.600	0.129	1.000	0.028
Soy Lecithin	4.006	1.500	0.060	1.500	0.060
Vitamin Premix-F2	1.527	0.500	0.008	0.500	0.008
Stay C - 35%	10.750	0.060	0.006	0.060	0.006
Choline Chloride 60%	1.400	0.290	0.004	0.290	0.004
Mineral Premix F-1	1.527	0.250	0.004	0.250	0.004
Calcium Phosphate monobasic (21%P)	0.730	1.500	0.011	1.500	0.011
Calcium Carbonate	0.048	0.010	0.000	0.010	0.000
L-Lysine 95%	2.900	0.350	0.010	0.350	0.010
MHA (methionine) 84%	2.900	0.380	0.011	0.380	0.011
Ethoxyquin, SQ mixture 6	5.280	0.020	0.001	0.020	0.001
Mold Inhibitor	1.800	0.020	0.000	0.020	0.000
Cellulose	2.600		0.000	3.000	0.078
Raw material cost of feed		100.00	2.349	100.00	2.298
Processors' gross margin[a]			0.507		0.496
Market price of feed			2.855		2.794

Sources: Authors' estimates based on the prices of ingredients gathered from the following sources. The prices of SPC and Omega-3 soybean oil are estimated as described in the text. fish meal and soybean oil prices are from the World Bank Pink Sheet; fish oil price is from FAO fishstat; the price of squid meal is from Altan (undated), the price of potato starch is the December 2013 online price from http://shop.honeyville.com/potato-starch-55lb.html. Other prices were obtained from personal communications with soybean processing personnel in Lincoln, Nebraska.

[a]EWOS (2013) reported that about 82.3% cost are accrued from raw materials such as fishmeal, fishoil, soy, while 17.7% are their gross margin, defined as the ratio between operating revenue and cost of raw materials.

[b]Assuming an omega-3 soybean oil premium of 40% above regular soybean oil. A premium of only 22% results in a reduction in the estimated market price of less than 0.3%.

Table 3: The discrete solution to the harvest problem using 2011 trial data (STA oil ration)

Age (s), Day	k*F(s)	M(s)= p* w(s)	Simple net return per year	Calculation of discounted annual net return				
				$R + M'$	V(s)=PV of M - PV of feed	c.r.f = r/(1-(1+r)$^{-s}$)	(c.r.f) × elapsed days	Every 365 days
	Cumulative cost ($/fish)	Sale Value ($/fish)		Simple marginal net benefit	PV of one cycle at this harvest age	Daily annuity	Opportunity cost for next period	c.r.f. × V(s)
21	0	0.61	10.53	0.606	0.60	0.029	0.604	10.50
43	0.120	1.36	10.50	0.631	1.22	0.029	0.629	10.43
71	0.525	3.59	15.75	1.826	3.00	0.043	1.194	15.57
99	1.123	6.21	18.74	2.020	4.93	0.051	1.415	18.44
128	1.925	9.47	21.53	2.466	7.26	0.058	1.674	21.07
168	3.099	13.38	22.35	2.737	9.76	0.059	2.379	21.71
196	4.174	16.86	23.62	2.398	11.93	0.063	1.751	22.82
239	5.890	20.19	21.85	1.620	13.24	0.057	2.462	20.89
261	6.715	22.23	21.70	1.213	14.25	0.057	1.245	20.66

Source: Authors' estimates.

Note: k=2.794 $/kg, p= 13 $/kg, c.r.f stands for capital recovery factor, annual interest rate, r=10%.

Table 4: The discrete solution to the harvest problem using 2011 trial data (traditional ration)

Age (s), Day	k*F(s)	M(s)= p* w(s)	Simple net return per year	Calculation of discounted annual net return				
				$R + M'$	V(s)=PV of M - PV of feed	c.r.f = r/(1-(1+r)$^{-s}$)	(c.r.f) × elapsed days	Every 365 days
	Cumulative cost ($/fish)	Sale Value ($/fish)		Simple marginal net benefit	PV of one cycle at this harvest age	Daily annuity	Opportunity cost for next period	c.r.f. × V(s)
21	0	0.54	9.44	0.543	0.54	0.026	0.542	9.42
43	0.120	1.32	10.22	0.660	1.19	0.028	0.612	10.15
71	0.405	2.79	12.28	1.185	2.34	0.033	0.931	12.14
99	0.745	4.14	12.52	1.007	3.30	0.034	0.945	12.32
128	1.088	5.43	12.37	0.943	4.17	0.033	0.962	12.11
168	1.707	7.66	12.94	1.619	5.65	0.034	1.378	12.57
196	2.350	9.79	13.86	1.483	7.00	0.037	1.027	13.39
239	3.546	12.83	14.17	1.839	8.60	0.037	1.599	13.57
261	4.207	15.29	15.49	1.799	10.20	0.040	0.891	14.78

Source: Authors' estimates.

Note: k= 2.855$/kg, p=13 $/kg, c.r.f stands for capital recovery factor, annual interest rate, r =10%.

Table 5: Estimated coefficients of the growth curve (equation 7), fix $\alpha = 3372$

	Estimates	Std. Error	Confidence interval (profile approach)	
			Lower (2.5%)	Upper (97.5%)
$\kappa_{11} = \kappa_{12}$	0.240*	0.009	0.221	0.258
κ_{14}	-0.028***	0.016	-0.059	0.004
$\tau_{11} = \tau_{12}$	5.961*	0.080	5.804	6.119
τ_{13}	0.977*	0.186	0.613	1.341

Notes: sample size was 64; *and *** indicates that the parameters are significant at the 1% and 10% level, respectively.

Table 6: Parameter estimates for the feed consumption curve (equation 9)

Coefficient	Estimates	Std. Error	Confidence interval (Profile approach)	
			Lower (2.5%)	Upper (97.5%)
$\gamma_{11} = \gamma_{12}$	13.972*	4.176	5.786	22.157
γ_{13}	50.013**	23.057	4.824	95.204
$\gamma_{21} = \gamma_{22}$	2.424*	0.149	2.133	2.715
γ_{23}	-0.636*	0.223	-1.072	-0.200

Notes: Total sample size is 62, fewer than for fish weight observation because of missing data.

* and ** indicate that the parameters are significant at the 1% and 5% level, respectively.

Table 7: Comparisons of results for producing 1 kg fish using alternative rations

	Model 1		Model 2	
	Traditional ration	STA oil ration	Traditional ration	STA oil ration
Price of fish ($/kg)	13.00	13.00	13.00	13.00
Price of feed ($/kg)	2.86	2.79	2.86	2.79
s* (age, months)	7.34	7.38	9.74	9.74
w^* (weight per fish, gm)	1643	1654	2250	2250
F^* (feed consumption, gm)	1752	1773	3478	3478
FCR (feed to gain ratio)	1.066	1.072	1.546	1.546
Feed cost ($/kg of fish)	3.04	2.99	4.41	4.32
Revenue ($/kg of fish)	13.00	13.00	13.00	13.00
Revenue minus feed cost ($/kg of fish)	9.96	10.01	8.59	8.68
Return per day ($)	0.045	0.045	0.029	0.030

Notes: s* denotes optimal harvest time (month); w* optimal harvest weight of a fish; F* denotes optimal level of feed consumed (kg/fish). Model 1 corresponds to the equations where asymptote is fixed at 3.372kg estimated from offshore data, model 2: calculate the age and consumption necessary for a 2.25kg fish (using the coefficients from Model 1).

Table 8: Comparison of various *Seriola* species growth rates in cage aquaculture operations

Mariculture species	Harvest size (kg)	Age (Month)	Growth rate (gm/Month)	Source
Greater amberjack (*Seriola dumerili)*	0.9–3	7–18	111–167	Chambers and Ostrowski (1999), Tucker (1998)
Yellowtail/almaco jack (*Seriola rivoliana/ mazatlana*)	1–3	9–18	83–250	Benetti et al. (1995b), Benetti (1997)
Japanese Hamachi (*Seriola quinqueradiata*)	1.5–7	12–24	125–292	Kafuku and Ikenoue (1992), Benetti et al. (2005)
Kingfish/yellowtail jack (*Seriola lalandi/dorsalis*)	1.5–3	8–13	153–230	Kolkovski and Sakakura (2007), Benetti et al. (2005)
Average growth			176	

Source: Adopted from Benetti, *et al.* (2010), page 199, Table 5.

Table 9: Budgets to produce 1 metric ton (1000kg) of fish

Cost items		Traditional ration					STA oil ration					% Change
	Price ($/Kg)	Share of feed by weight (%)	Quantity (kg)	Value ($)	Share of feed cost	Share of total cost	Share of feed by weight (%)	Quantity (kg)	Value ($)	Share of feed cost	Share of total cost	
SPC	2.555	40.00	618.34	1579.99	0.432	12.15	40.00	618.34	1579.99	0.445	12.27	0.0
Fishmeal	1.480	11.89	183.80	321.10	0.088	2.47	11.89	183.80	321.10	0.090	2.49	0.0
Fish oil	2.042	17.30	267.43	546.09	0.149	4.20	8.65	133.72	273.05	0.077	2.12	-50.0
STA oil	1.479	1	15.46	22.88	0.006	0.18	8.65	133.72	197.87	0.056	1.54	765.0
Other ingredients	2.569	29.81	460.82	1183.81	0.324	9.11	30.81	476.27	1180.18	0.332	9.17	-0.31
Raw materials of feed cost		100.00	1545.84	3653.86	1.000	28.11	100.00	1545.84	3552.19	1.000	27.59	
FPC and processors' margin				788.10		6.06			766.17		5.95	
Labor				2416.67		18.59			2416.67		18.77	
Fingerlings				1985.42		15.27			1985.42		15.42	
Company's own costs				4155.96		31.97			4155.96		32.28	
Total cost				13000					12876			**-0.95**

Note: FPC stands feed processing cost.

Table 10: Potential global market sizes for STA oil

Mariculture species that can be fed STA oil ration		Scientific name[g]	Annual farmed production[h] (mt)	Potential Market Size			
				STA oil (mt)	Raw soybeans for STA oil (mt)	Raw soybeans for STA oil (bu)	Acres of STA beans
Yellowtail species	Longfin yellowtail	*Seriola rivoliana*	466	62	350	12,871	306
	Amberjacks	*Seriola spp*	139,389	18,638	104,710	3,847,049	91,596
	Japanese amberjack	*Seriola quinqueradiata*	148,582	19,868	111,617	4,100,792	97,638
	Greater amberjack	*Seriola dumerili*	2,567	343	1,928	70,851	1,687
	Lesser amberjack	*Seriola fasciata*	3	0	2	83	2
	Sub-total		291,007	38,912	218,608	8,031,646	191,230
Farmed Salmon	Farmed Atlantic salmon	*Salmo salar*	1,436,283	192,053	1,078,951	39,640,642	943,825
	Other farmed salmon		159,587	21,339	119,883	4,404,516	104,869
	Sub-total		1,595,870	213,392	1,198,834	44,045,158	1,048,694
Total	Yellowtail + farmed Salmon		1,886,878	252,305	1,417,442	52,076,804	1,239,924

Notes: [g]Corresponds to the FAO definition. Source: FAO (2014), average of 2010-2012 years. Global production of salmon (Atlantic, Australian, Pacific, Chinook, Chum, Coho, Masu, Pink, Sockeye species are considered) is about 2,872,566 metric tons (mt) (2010-2012 average). About, 50% of global salmon is farmed Atlantic salmon, which constitutes above 90% of the farmed salmon market (Curieux-Belfond et al. 2009)

Producing 1 mt of fish would require 197.87 kg (0.198 mt) of STA oil (Table 9). Soybeans to STA oil conversion rate are assumed same as the conversion rate between soybeans and soybean oil, 0.178. 1 mt soybeans = 36.74 bushels. Yield of STA-enhanced soybean is assumed 42 bushels per acre.

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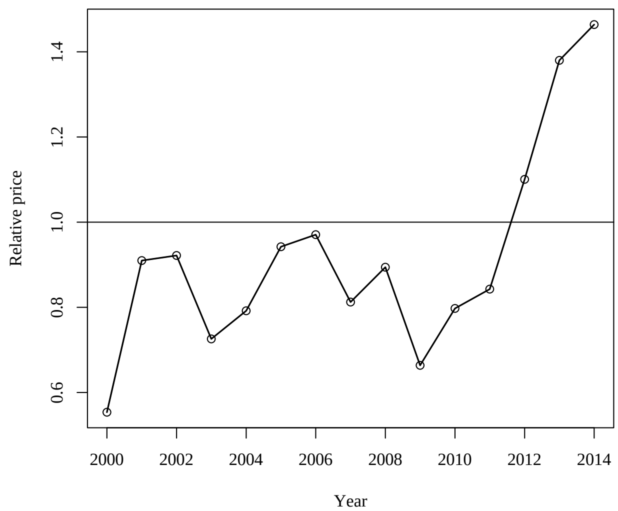
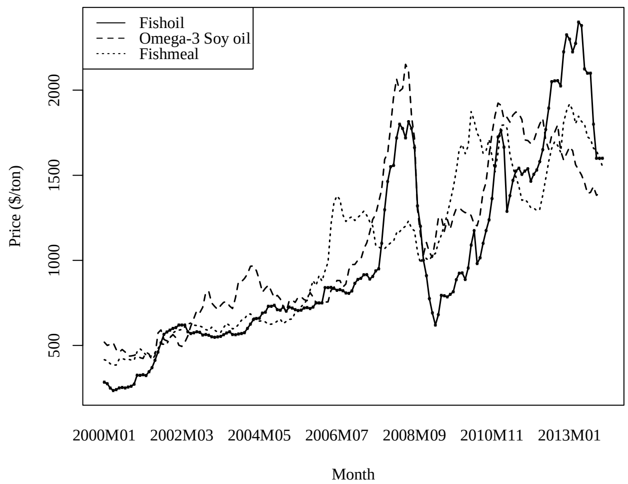
Figure 1: Relative price of fish oil (FO) to possible Omega-3 soybean oil (soybean oil plus 40% premium), 2000-2014



Source: Prices of Omega-3 soybean oil are estimated from the prices of regular soybean oil gathered from the World Bank Commodity Price Data (The Pink Sheet); Fish oil prices are gathered from FAO Globefish 2009, and http://www.fao.org/economic/est/prices.
Note: For soybean oil (any origin), crude, f.o.b. ex-mill Netherlands; and for fish oil (any origin) international market prices (monthly averages) CIF N.W. Europe are considered.

Figure 2: Comparison of prices for fishmeal, fish oil and estimated price for Omega-3 soybean oil[a]



[a]Omega-3 soy oil is estimated here at 140% of soybean oil.

Source: The World Bank Commodity Price Data (The Pink Sheet) and FAO globe fish.

Figure 3: The fitted regression lines for body weight (left panel) and cumulative feed intake (right panel)