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Economic feasibility of high Omega-3 soybean oil in mariculture diets: A sustainable replacement for fish oil.

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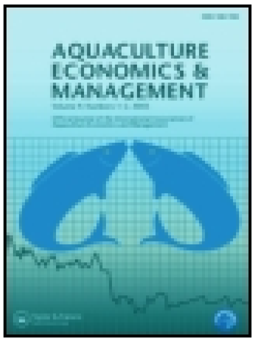

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Economic feasibility of high Omega-3 soybean oil in mariculture diets: A sustainable replacement for fish oil

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ABSTRACT

The growth of global aquaculture has put intense pressure on sources of fish oil and fishmeal for aquafeeds. The nutraceuticals industry has added further pressure on fish oils with high Omega-3 fatty acids. GM soybeans could provide substitutes in high Omega-3 soybean oil (STA oil), as well as soy protein concentrate (SPC). This article examines the technological and economic feasibility of substituting STA oil for one-half the fish oil in the diet of *Seriola rivoliana*, a species often destined for sushi markets. Previous studies have shown that the substitution results in no change in flesh quality or consumer acceptance. We find that the two feed technologies result in essentially identical growth pattern and feed consumption. Economic feasibility depends upon the price of STA oil being lower than the price of fish oil. Based on our market analysis, we estimate that STA oil will enter the market at a price about two-thirds of the fish oil price. The estimated cost savings at these prices are small, a 2.8% reduction in feed costs and 0.9% reduction in total costs. However, the potential global market for STA oil could be as much as 252 thousand metric tons annually, which would require soybean production equivalent to that from 1.63% of current U.S. soybean area.

KEYWORDS

Aquaculture; asset replacement principles; diets/rations; genetically modified (gm); Omega-3 soybean oil (STA oil)

Introduction

Global aquaculture production (finfish and crustaceans) doubled between 2000 and 2012 (Food and Agricultural Organization (FAO), 2013, 2014), while production of compounded aquaculture feed from the feed industry increased about fivefold (Tacon, 1997; Alltech, 2013). Because fishmeal and fish oil are primary components in aquafeed for most species, the rapid growth of aquaculture, combined with rising nutraceutical demand is putting pressure on the fisheries that provide these components (Shepherd & Bachis, 2010), thus increasing fish oil prices relative to high Omega-3 soybean oil prices (Figures 1 and 2).

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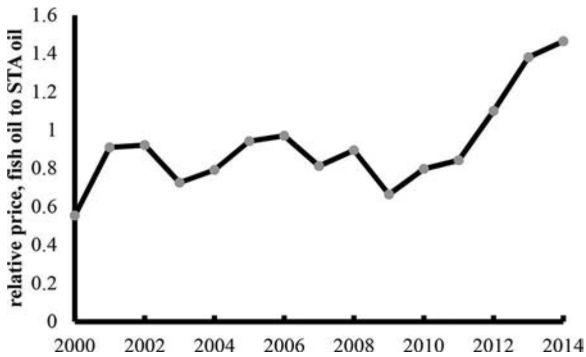

Figure 1. Relative price of fish oil (FO) to possible Omega-3 soybean oil (soybean oil plus 40% premium), 2000–2014. *Source*: Prices of Omega-3 soybean oil are estimated from the prices of regular soybean oil gathered from the World Bank Commodity Price Data (The Pink Sheet); Fish oil prices are gathered 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.

Previous experiments have shown that soy protein concentrate (SPC) can successfully replace fishmeal in the diets of aquaculture (Hamlet Protein, 1995, 1997; Kaushik et al., 1995; Refstie et al., 1998; Mambrini et al., 1999; Dersjant-Li, 2002; Forster et al., 2002; Cremer et al., 2006; Caditec Testing S.L., 2007, 2008; Cremer et al., 2007, 2008; Lan et al., 2007; Drawbridge et al., 2008a, 2008b; Sookying and Davis, 2011; Davis, undated; Hart & Brown, Undated). Recent experiments with genetically engineered/modified (GM)

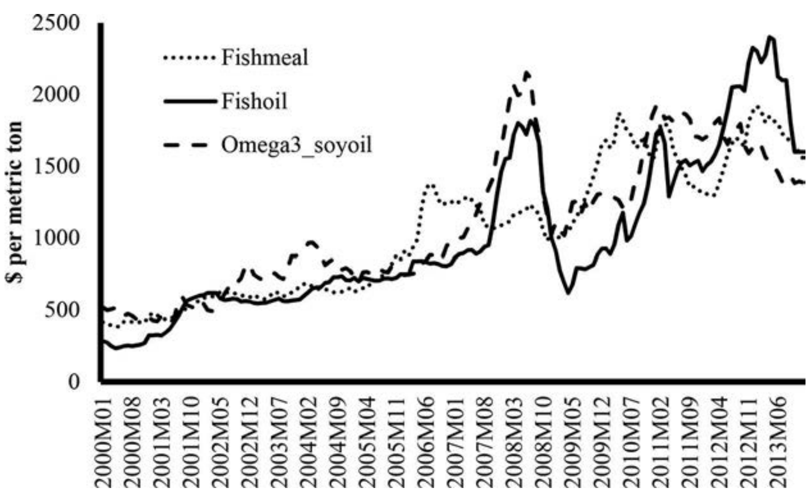

Figure 2. Comparison of prices for fishmeal, fish oil and estimated price for Omega-3 soybean oil[a]. *Note*: Authors' calculation based on data collected from The World Bank Commodity Price Data (The Pink Sheet) and FAO globefish 2009. Omega-3 soybean oil is estimated here at 140% of soybean oil.

soybean oil rich in Omega-3 fatty acids, or STA oil, (from stearidonic acid, Eckert et al., 2006) demonstrate that this new oil source can successfully replace up to 50% of fish oil in these diets (Clemente, 2011, 2013). Flesh content of Omega-3 fatty acids is not reduced, and consumer panel taste tests by the Food Innovation Center of Oregon State University showed that consumers could not tell a difference between the fish fed the STA oil versus traditional diets (Clemente, 2011).

The substitution of STA oil in aquaculture diets would result in increased demand for soybeans and reduced pressure on anchovy and other fisheries that currently provide fish oil. In this study, we examine the feasibility and potential implications of the inclusion of STA oil into the diets of the *Seriola 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 we utilize experimental data to examine optimal harvest ages and economic performance using the two diets.

Data and methods

Experimental data

Data from six experimental trials are used to predict growth in 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 over several years (2005 to 2013) as well as over different lengths of time (50 to 330 days) (Table 1).

Experimental treatments consisted of the following rations: (i) one of two traditional rations based on fish oil (Commercial A or Commercial B, compounded by two different suppliers), 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 nearly match 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 ratio is much better for STA oil diet than traditional diet and in some cases the reverse. We pooled all the data, with indicator variables for ration and location, for a statistical analysis of growth

Table 1. Descriptive statistics of experiments used in this study.

Year and type	Treatment	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 (STA oil and traditional) 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. Note that average growth and feed consumption levels were used for offshore experiments, as experiment-wise data were unavailable. We 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 tanks were not equal under the STA oil vs traditional rations. The 2012a STA oil experiment was stopped at 79 days, while 2012a Traditional B was continued up to 261 days.

and feed consumption, and used these results to estimate cost and benefits of STA oil to replace fish oil.

Feed ingredient prices

The economic feasibility of substituting STA oil for fish oil will depend on prices as well as fish performance. We use 2013 prices for this analysis, from sources we report in Table 2, except for fish oil, for which we use a higher price to reflect the increasing trend of fish oil price relative to STA oil. There is no STA oil on the market, so we estimate its price as 140% of the commodity soybean oil price, based on the analysis of Perrin and Fulginiti (2011), which determined that the extra cost of identity preservation and segregation (IPS) could require as much as 40% premium over regular soybean oil. Given the 2013 world price for soybean oil of $1,056 per metric ton, this yields an estimate of the 2013 STA oil price at $1,478 per metric ton. The 2013 world fish oil price was $2,042 per metric ton, equal to 1.38 times this STA oil price. However as illustrated by Figures 1 and 2, this price ratio has been rising and according to the analysis of Shepherd and Bachis (2014), it can be expected to continue to do so. To provide an economic evaluation relevant to substitution of STA oil for fish oil in the future, we use a fish oil price 1.5 times the STA oil price, rather than the 1.38 times as observed in 2013, which is $2,217 per metric ton.

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

		Ration			
		Traditional		STA Oil	
Ingredient	Ingredient price ($/kg)	Quantity (%)	Cost ($/Kg)	Quantity (%)	Cost ($/Kg)
Procon 2000 (SPC) 68.9/0.8	2.555	40.000	1.022	40.000	1.022
Fish meal, anchovy 71.6/7.8	1.747	11.890	0.208	11.890	0.208
Fish oil	2.217	17.300	0.384	8.650	0.192
STA soybean oil	1.478[a]			8.650	0.128
Others	2.486	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			3.000	0.078
Raw material cost of feed		100.00	2.3791	100.000	2.3128
Margin (21.5% markup[b])			0.512		0.497
Market price of feed			2.8907		2.8102

Sources: Authors' estimates based on the prices of ingredients gathered from the following sources. The prices of SPC and STA 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]Assumes an Omega-3 soybean oil premium of 40% above regular soybean oil. (A premium of only 22% would result in a reduction in the estimated market price of less than 0.3%).

[b]EWOS (2013) reported that about 82.3% of cost is 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.

In the absence of a reliable 2013 price for SPC, we estimate it as 4.7 times the price of soybean meal (the average ratio of SPC to soybean meal price from five different reports of SPC price between 2000 and 2009, from Hardy, 2000; Forster et al., 2002; Schmalz, 2007; Griffis, 2008; Weingartner & Owen, Undated). The resulting estimate of SPC price for 2013 is $2,555 per metric ton, which is about 46% higher than 2013 fishmeal price, $1,747 per metric ton (World Bank, 2014).

Table 2 lists the inclusion levels of ingredients and their costs to produce one kg of each ration, using 2013 ingredient prices. Our estimate of the market price of the STA oil aquafeed (after adding processors' gross margin) is $2.81 per kg versus $2.89 per kg for the traditional ration, a cost reduction of 2.8%.

Methods

Fish growth and feed consumption functions

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

$$y_{it} = E(y_{it}|x_{it}) = f(x_{it}, \theta) \quad (1)$$

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. These authors 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, we compared the goodness of fit for three models (Bertalanffy, logistic, and Gompertz) and found the Gompertz model to provide the best fit, which we selected for fitting the growth of *S. rivoliana*.

Substituting the Gompertz function into Equation (1), we specify the growth regression as:

$$w_{it} = \alpha \exp(-\exp(-\kappa(s_{it} - \tau))) + \varepsilon_{it} \quad (2)$$

where, w_{it} is the weight per fish with treatment i, t is the time elapsed since the beginning of the trial, s_{it} is the age of the fish at time t, α is the upper asymptote, κ is the growth rate, τ is the inflection point, and ε_{it} is a 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 & Watts, 1988). We 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, we use the power function (subscripts i and t suppressed for simplicity):

$$F = \gamma_1 s^{\gamma_2} + \varepsilon \quad (3)$$

where F is cumulative feed intake through age s, γ_1 is the intercept, γ_2 expresses the rate of increase in feed intake, and ε is a random term.

Optimal harvest age using the asset replacement principle

We 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, p. 60).

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

$$R(s^*) + M'(s^*) = \rho M(s^*) \tag{4}$$

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:

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

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

Results

Fitted growth and consumption functions

To allow for different growth and consumption paths for the two diets, we introduce an indicator variable D_1, equal to 1 for the traditional ration, 0 for the STA oil. We introduce another indicator variable, D_2 for location, equal to 1 for the offshore trials, 0 for tank trials. We use R (Fox & Weisberg, 2011) to estimate this modification of Equation (2):

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

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 help us to calibrate the growth path to heavier weights. We found that the ration indicator D_1 affects neither growth path nor consumption path significantly, while the location indicator D_2 affects both.

The coefficients associated with the ration indicator D_1 were not significantly different from zero at the 5% level[1]. This indicates that there is no significant difference in growth path resulting from the STA oil versus traditional ration. However, the location indicator D_2 significantly affected the asymptote parameter α_{13}, resulting in an estimated asymptote for offshore production[2] of 3.372 kg. Given that the fish in these trials are the same genetically, we assume that the growth asymptote must be the same, even though the path to that asymptote may differ between tank production and offshore production. We thus re-estimate the growth function consistent with this estimate of offshore growth asymptote, using the following specification:

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

Estimates are shown in Table 3, and the growth path is illustrated in Figure 3.

We modify Equation (3), again using the indicator variables D_1 and D_2, to estimate the path of feed consumption:

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

Consumption parameters associated with the ration indicator D_1 (γ_{12} and γ_{22}) were insignificant, indicating that ration had no significant effect on consumption, while parameters for the location indicator D_2 were significantly different from zero[3]. We therefore fit a common feed consumption curve for STA oil and traditional rations:

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

Statistical results are shown in Table 4, and illustrated in Figure 3.

The estimated feed conversion rate (FCR) at a harvest weight of 2.25 kg is 1.546. For comparison, estimates of the FCR for Japanese yellowtail (a *Seriola*

Table 3. Estimated coefficients of the growth curve [Equation (7)], fix $\alpha = 3372$.

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

Notes: sample size was 64.
*** Indicate that the coefficients are significant at the 1% level.

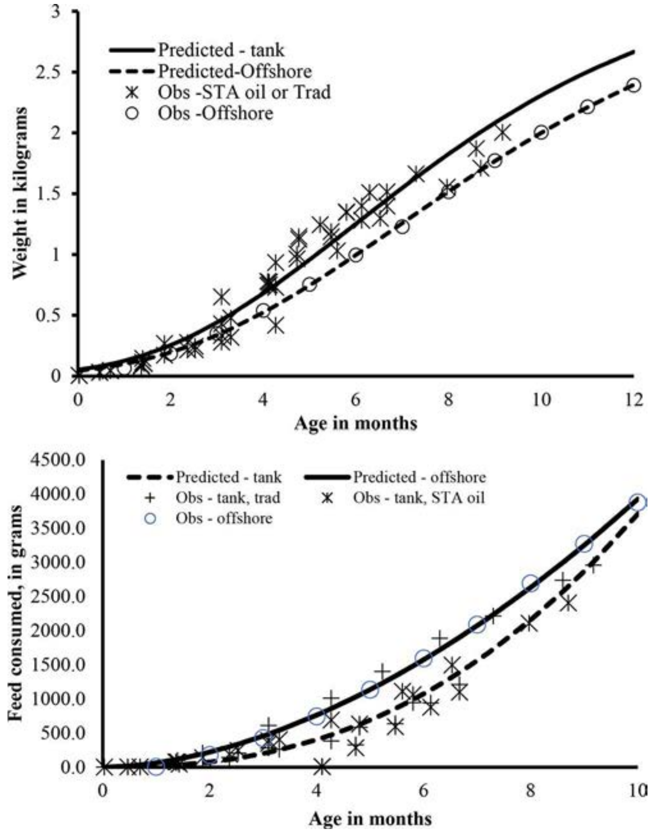

Figure 3. The fitted regression lines for body weight (upper panel) and cumulative feed intake (lower panel).

species) fed pelleted feeds in studies from 1993 to 2012 (Watanabe et al., 1993; Nakada, 2008; Benetti et al., 2005; Kofuji et al., 2006; Moran et al., 2009; Kankainena, 2012) suggest that FCRs vary considerably (1.1 to 4.8) because of variation in feed, feeding practices, and harvest age (Miranda & Peet, 2008).

Economic considerations

Table 5 compares optimal management results under the two rations with two possible scenarios, an "optimal" harvest weight if fish could be sold for $13

Table 4. Parameter estimates for the feed consumption curve [Equation (9)].

			Confidence interval (Profile approach)	
Coefficient	Estimates	Std. Error	Lower (2.5%)	Upper (97.5%)
γ_{11}	13.972***	4.176	5.786	22.157
γ_{13}	50.013**	23.057	4.824	95.204
γ_{21}	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 observations because of missing data.
***, ** Indicate that the coefficients are significant at the 1%, 5% level, respectively.

Table 5. Comparisons of results for producing 1 kg fish using alternative rations.

	For "optimal" harvest weight[a]		For commercial standard harvest weight	
	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)	2.89	2.81	2.89	2.81
s (harvest age in months)	7.34	7.38	9.73	9.73
w (weight per fish in grams)	1643	1654	2250	2250
F (feed consumption in grams)	1752	1773	3472	3472
FCR (feed to gain ratio)	1.066	1.072	1.543	1.543
Feed cost ($/kg of fish)	3.04	2.98	4.459	4.336
Revenue ($/kg of fish)	13.00	13.00	13.00	13.00
Revenue minus feed cost ($/kg)	9.96	10.02	8.541	8.664
Return per day ($)	0.045	0.045	0.029	0.030

[a]The weight that maximizes return if the price of fish is $13/kg for all harvest weights.

per kg for any weight of fish, and the commercial standard harvest weight. We calculate optimal harvest weight based on the ration prices estimated above, and the "in-tank" value of these fish of $13 per kg (Neil Sims of Kampachi Farms, personal communication, 2013). Note that Kamstra (2013) reported that market price per kg of yellowtail kingfish is about $17.50 (14 Euro), while Nakada (2008) reported that the price of 600 g of amberjack is $14.30. We substitute the estimated coefficients from Equations (7) and (9) into Equation (5) to solve for the optimal harvest age (model 1). These optimal harvest ages (7.34 and 7.38 months) and harvest weights (1.643 and 1.654 kg) differ slightly between the two rations because feed price differs. The previous studies of the *Seriola* species grown in aquacultures around the world (Table 6) suggest that fish can even be harvested at a weight as low as 1.0 kg.

The "optimal" harvest weights calculated above assume that fish price is constant regardless of the weight of the fish marketed. However, *S. rivoliana* for the sushi market is actually harvested at the weight of 2.25 kg because of consumers' preferences (Neil Sims of Kampachi Farms, personal communication, 2013). To approximate the results of commercial sushi production,

Table 6. 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. (1995); 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 rate			176	

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

Table 7. Budgets to produce 1 metric ton (1000 kg) of fish.

		Traditional Ration			STA Oil Ration			
Item	Price ($/kg)	Share of feed by weight (%)	Quantity (kg)	Value ($)	Share of feed by weight (%)	Quantity (kg)	Value ($)	Percent change
SPC	2.555	40.0	617	1576.96	40.0	617	1576.96	
Fishmeal	1.747	11.9	183	320.51	11.9	183	320.51	
Fish oil	2.217	17.3	267	591.81	8.7	133	295.90	
STA oil	1.478				8.7	133	197.27	
Other (traditional)	2.486	30.8	475	1181.64				
Other (STA ration)	2.478				30.8	475	1178.02	
Feed ingredient sum		100.0	1543	3670.92	100.0	1543	3568.67	−2.8%
Feed processor margin				649.75			631.65	
Labor				2416.67			2416.67	
Fingerlings				1985.42			1985.42	
Other producer expenses				4277.23			4277.23	
Total cost				13000.00			12879.65	−0.9%

we therefore calculate the age consistent with a 2.25 kg body weight to be 292 days using the estimated coefficients, and the feed to gain ratio of 1.543. The feed cost per kg of fish produced is 2.8% cheaper for STA oil diet.

Given our estimate of ration prices ($2.81/kg for STA oil, $2.89/kg for traditional) and fish prices ($13.00/kg), the estimated return over feed cost for the STA oil diet is $8.66 per kg of fish compared to $8.54 per kg of fish returns under the commercial diet (Table 5). Note that our estimate of fish price is the price of fish in tank (Neil Sims of Kampachi Farms, personal communication, 2013). Given this fish price of $13 per kg, we find that 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 a time-discounted basis. Given these results, the adoption of STA oil for aquafeed appears to be economically feasible, increasing returns over feed cost by about 1.45% at 2013 prices. We expect that, with rising prices of fish oil versus soybean oil, the substitution will be more economically desirable as time passes.

Feed costs represent about one third of the market value of these fish. In Table 7 we report the estimate of total production costs per metric ton of fish using the two rations. We 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 5. We estimate fingerling/juvenile costs to be $2.00 per kg of fish produced, which was based on the estimates provided by Kamstra (2013) and Nakada (2008). Kamstra (2013) also provides an estimate of labor cost at about $1.50 per kg of fish. Helsley (1999) estimated labor cost to be about $3.33 per kg of fish produced, based on a demonstration project on cage culture of *Polydactylus sexfilis*. We use the average as the estimate of labor cost, $2.42 per kg of fish produced. Other capital, management and transportation costs we 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 2.8% and total cost by about 0.9% (Table 7).

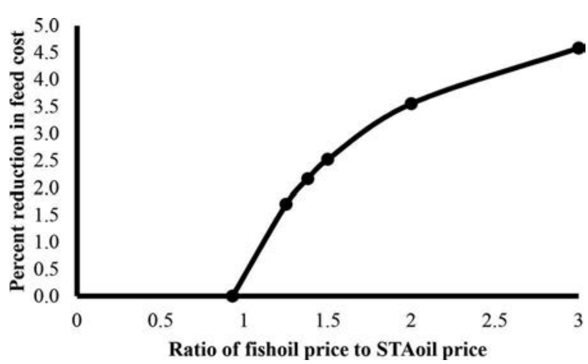

Figure 4. Effect of fish oil: STA oil ratio on feed cost.

Table 8. Potential global market sizes for STA oil.

Mariculture species that can be fed STA oil ration		Scientific name ‡	Annual farmed production† (mt)	Potential Market Size			
				STA oil (mt)	Raw soybeans for STA oil (mt)	Raw soybeans for STA oil (bu)	Areas of STA beans (Ha)
Yellowtail species	Longfin yellowtail	*Seriola rivoliana*	466	62	350	12,871	124
	Amberjacks	*Seriola spp*	139,389	18,638	104,710	3,847,049	37,069
	Japanese amberjack	*Seriola quinqueradiata*	148,582	19,868	111,617	4,100,792	39,514
	Greater amberjack	*Seriola dumerili*	2,567	343	1,928	70,851	683
	Lesser amberjack	*Seriola fasciata*	3	0	2	83	1
	Sub-total		291,007	38,912	218,608	8,031,646	77,390
Farmed Salmon	Farmed Atlantic salmon	*Salmo salar*	1,436,283	192,053	1,078,951	39,640,642	381,961
	Other farmed salmon		159,587	21,339	119,883	4,404,516	42,440
	Sub-total		1,595,870	213,392	1,198,834	44,045,158	424,401
Total	Yellowtail + farmed Salmon		1,886,878	252,305	1,417,442	52,076,804	501,790

Source: FAO (2014), average of 2010–2012 years.

Notes: ‡Corresponds to the FAO definition. †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 of STA oil (Table 7). 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 104 bushels per hectare.

This benefit is calculated on the basis of a fish oil to STA oil price ratio of 1.5, given that we expect this price ratio to be relevant in the near future. It is useful to examine how the benefits of the STA oil diet change as fish oil prices rise relative to STA oil. The 2013 breakeven price ratio is 0.99, that is, fish oil could have been as low as $\$1,478 \times 0.99 = \$1,463$ per metric ton, rather than the observed $2,402, before it would become uneconomical to replace it with STA oil at $1,478 per metric ton. Figure 4 illustrates how the total cost savings increase with an increase in the price ratio of fish oil to STA oil, reaching a level of 3.5% should fish oil price rise to three times the level of STA oil price.

Implications of aqua-industry adoption of STA oil diets

This study was conducted for *S. rivoliana*, a minor aquaculture-produced species as used for sushi production. Results could be similar for other species, perhaps including farmed Atlantic salmon. Although dietary responses of species differ, we consider what might be the implications if farmed salmon diets could be similarly adapted for use of STA oil. Farmed salmon diets already include 2/3 of oil in the ration from rapeseed rather than fish oil but the quality of the fish has deteriorated accordingly (Shepherd & Bachis, 2014). Thus there is potential for replacing some or all of the rapeseed oil to restore Omega-3 fatty acid levels in the salmon that is produced. We also note that regulatory issues may arise in using STA-oil in some aquaculture markets because of GMO concerns. We estimate the potential aquaculture market for STA oil by considering a number of species, as shown in Table 8.

Based on current global aquaculture production of various *Seriola* species alone, potential STA oil demand could be as much as 39,000 metric tons per year, which could be supplied by about 77,000 hectares of GM soybeans. Adding to this the potential feed requirements of farmed Atlantic salmon raises the total potential demand to 252,000 metric tons, which would require production from approximately one-half million hectares of soybeans (about 1.63% of current U.S. soybean acreage). We again note that these are maximum numbers for each species. Ultimate amounts fed will be limited by reductions in the amount substituted to accommodate some reduction in product quality, and to some extent by regulatory issues.

Conclusions

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 therefore depends 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 the 2013 soybean oil price, this implies a price of $1,478 per metric ton of STA oil, versus $2,217 per metric ton for fish oil when the latter is adjusted to 1.5 times the price of the former, the minimum ratio we expect to prevail in the future. But given our results, the substitution would have been economically feasible at any fish oil price down to $1,463 per ton. Because fish oil represents only 12% of the ration cost, and only half of that would be replaced with a cheaper ingredient, cost savings at current prices are small (about 2.8% of feed cost, 0.9% of total cost).

We 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 could be as high as 252,000 metric tons annually, which would require about half million hectares of GM soybeans high in Omega-3 oils, equivalent to 1.63% of U.S. soybean area. However, less than this potential will be realized because diets for some species may not be adaptable to STA oil, because of limited substitution to maintain fish quality, and because of likely regulatory considerations in some circumstances. 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, though the aquaculture industry would be based on more sustainable footing. Estimates of the sizes of these welfare gains and losses remain to be explored.

Notes

1. $\alpha_{12} = 390.76^{**}$ (197.14); $\kappa_{12} = -0.035^{**}$ (0.072); $\tau_{12} = 0.397$ (0.286); standard errors in parentheses (** significant at 5%).
2. $\alpha_{11} = 1865.7$ (136.3); $\alpha_{13} = 1506.4$ (461.5); standard errors in parentheses. Estimated offshore asymptote is thus $1865.7 + 1506.5 = 3372.1$.
3. $\gamma_{12} = 4.76$ (8.64); $\gamma_{22} = -0.10$ (0.31); standard errors in parentheses.

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