The Values of Whole Algae and Lipid Extracted Algae Meal for Aquaculture

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ABSTRACT

This research applies hedonic pricing methods to value whole algae and lipid-extracted algae (LEA) for aquaculture. Prices and nutritional characteristics for commonly applied aquaculture feed ingredients are used to determine the values of whole algae and LEA based on their nutrient compositions. The results show that whole *Chlorella pyrenoidosa* will have a higher value than soybean meal and a lower value than menhaden fishmeal. Results show that whole *Nannochloris oculata* and *Nannochloris oculata* LEA will have a lower value than both soybean meal and menhaden fishmeal.

Keywords: aquaculture; fishmeal; whole algae; lipid-extracted algae; hedonic valuation

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1. INTRODUCTION

1.1 General Overview

Aquaculture is one of the most aggressively growing sectors in global agriculture; it is expanding more rapidly than all other animal food producing industries [1,2,3]. The production of food fish from aquaculture has increased at an average annual growth rate of 8.8% worldwide over the last 30 years [3,4]. It is forecasted that by 2022, aquaculture will provide an additional 22 million tons of fish, which translates into approximately a 35% increase compared to the current production [4] and by 2030, it is anticipated that an additional 40 million tons of aquatic food will be required for human consumption [2].

Currently, fishmeal is the most important nutrition-feed ingredient used in aquaculture diets. There are two primary reasons for fishmeal being so popular in aquaculture diets: it has high protein content and a virtually ideal amino acid profile for most aquatic species. As aquaculture has been rapidly expanding, the demand for fishmeal has been increasing as well. Since fishmeal production depends primarily on wild stocks of pelagic species, it relies heavily on external factors. However, the global supply of fishmeal remains static and is expected to remain stable in the future [5,6,7]. Shields and Lupatsch [8] underline the fact that the source of fishmeal in aquaculture is finite and due to increased prices of fishmeal and fish oil there has been a growing interest in viable alternatives to fishmeal. The alternative feed ingredients that have been considered so far are both plant based and animal based. Those include but are not limited to: soybean meal, linseed meal, corn gluten meal, meat and bone meal, and hydrolyzed feather meal.

Algae have also been considered to be potentially viable alternative feed ingredients for

aquaculture. Algae have attractive properties as a candidate to replace meals, because they are rich in protein and carbohydrates, which are necessary components in human and animal diets. Algae also contain a high percentage of lipids which are crucial in aquaculture diets. Moreover, Brune [9] mentions that algae could increase aquaculture production 3 to 4-fold and reduce its production costs by \$0.05 to \$0.1 per pound.

1.2 Statement of the Problem

Since no market exists for whole algae or LEA, the prices are not observed. Thus the economic feasibility of algae production is difficult to analyze, given the uncertain value of potential co-products.

1.3 Objective

The objective of this study is to estimate the approximate value of whole algae and lipid extracted algae (LEA) meal as an aquaculture feed using hedonic pricing techniques. Hedonic models offer a statistical method for estimating the implied market value for the components of a product, based on the market price for the product and the proportion of each component in the final product. In this study a hedonic model is estimated for commercially available feedstuffs (e.g., soybean meal, corn, fishmeal, etc.) to calculate what the market place paid for (or valued) the nutrients (such as: energy, protein, and amino acids) in these feedstuffs. By estimating the implied values for energy, protein, amino acids and other nutrients, which are important in aquaculture feeds, a hedonic modeling approach can estimate the value or price that the feedstuff market would have placed on LEA. Eighteen different feed meals are used to estimate the hedonic model for nutrients in LEA that are important to aquaculture.

2. LITERATURE REVIEW

2.1 Introduction

Current fishmeal production limits and price fluctuations suggest that reduced reliance on fishmeal would be desirable. As discussed earlier, the fishmeal production over the past decade has been stable, even though aquaculture has been growing significantly. Fishmeal production resources are currently utilized at capacity, which significantly limits the possibility of expansion in the future. Researchers have anticipated the problem for three decades, and a potential substitute for fishmeal has been aggressively sought. Over this time, there has been extensive research; however no suitable solution has been found. For example, the raising of salmon and shrimp requires feed containing large amounts of high value proteins and lipids (in particular the omega-3 fatty acids), which are mostly provided by fishmeal. As described below, it is possible to reduce the dependence on fishmeal, although total substitution of fishmeal with other ingredients is highly unlikely without affecting the growth performance of fish or shrimp.

2.2 Potential Substitution of Fishmeal by Various Ingredients

Aquacop and Cuzon [10] discussed the importance of different types of ingredients for shrimp feed. The authors mention major components of shrimp feed which include soybean meal, yeast, shrimp meal, and fishmeal. Fishmeal was found to be the major component in the feeding diet. They find that there is a possible indication of antinutritional effects of large amounts of soybean meal. The replacement of fishmeal in shrimp feed does not affect growth rates up to 20 percent inclusion. Their results showed that beyond this level, minor negative effects were observed. Their analysis concluded that an optimal shrimp feeding diet consisted of

30-40% of fishmeal, 7-15% shrimp meal, 5-15% soybean meal.

Kikuchi [11] conducted feeding experiments to study the potential replacement of fishmeal with the combinations of soybean meal, blood meal, corn gluten meal, and freeze-dried meat of blue mussel in the diet of Japanese flounder. The author concluded that up to 45% of fishmeal protein can be replaced with combination of other protein sources without affecting the growth performance.

Ma et al. [12] conducted two 8-week trials to examine the effect of replacing fishmeal with poultry by-product meal and soybean meal on juvenile golden pompano, *Trachinotus ovatus*. The authors concluded that more than 21% of fishmeal must be retained in diets when these meals are used alone as a fishmeal substitute.

Smith et al. [13] show that low-ash meat meals have the greatest potential to replace fishmeal in shrimp diets. The authors conclude that meat meal can replace approximately half of the digestible crude protein, and dehulled lupins can replace a quarter of the digestible crude protein in a shrimp diet without significantly affecting biological performance.

2.3 Potential Substitution of Fishmeal by Algae

Olivera-Novova et al. [14] conducted a study to evaluate the use of microalga *Spirulina maxima* as a fishmeal replacement in practical diets for tilapia, with the objective of evaluating its nutritional quality and determining the best substitution level. Their experiment included five formulated diets using the microalga spirulina to substitute for 20%, 40%, 60%, 80%, and 100% fishmeal. The substitution effect was compared to the diet in which the fishmeal was the sole protein source. Each diet was formulated to provide 35% protein and 10% lipids. The treatment was studied for 9 weeks and the results indicated that the growth rate and protein utilization of

fish fed the diet with 20% and 40% *Spirulina* were not significantly different from the fishmeal source diet. The study showed that the further increase in the alga protein content at the expense of fishmeal significantly decreased the growth and feeding performance. The authors conclude that *Spirulina* can replace up to 40% of the fishmeal protein in tilapia diets without any adverse effects and suggest that the plant proteins in general could have a lower dietary quality than fishmeal.

Similar results were obtained by Tartiel et al. [15] where they examined the effect of partial replacement of fishmeal with dried microalgae (*Chlorella spp* and *Scenedesmus spp*) in Nile tilapia (*Oreochromis niloticus*) diets on fish growth performance. Nine different diets were formulated and the results indicated that algae could be utilized in tilapia diets up to 50% instead of the dietary ingredient without adverse effects on fish growth performances, feed utilization parameters and body composition.

Hanel et al. [16] conducted an eleven-week trial to evaluate the growth effect of partial replacement of fishmeal by the microalgae *Spirulina platensis* in the diet of juvenile Pacific white shrimp *Litopenaeus vannamei* (Boone). Three experimental diets and a reference diet were used: microalgae *Spirulina plantesis* diet, commercial carp feed diet, bacterial mud feed diet, and commercial fish feed as a reference diet (used 43.2% of fishmeal). Their results indicated that *Spirulina*-fed shrimp showed the highest final weight, followed by commercial fish feed, carp feed, and bacteria diet fed shrimp, although *Spirulina plantesis* diet still contained 10% of fishmeal. Moreover, *Spirulina*-fed shrimp showed stronger pigmentation than any other diets. However the authors suggest that, some kind of nutritional factors like minerals and vitamins further add up to the good nutritional quality of the algae.

Muller-Feuga [17] investigated the nutritional role of microalgae in aquaculture for

different species and their analyses showed the positive results when the following species were used: *Skeletonema*, *Chaetoceros*, *Tetraselmis*, *Chlorella* and *Isochlorysis*. Apt and Berhens [18] mention microalgae as a commercial source of polyunsaturated fatty acids, and even of energy, high quality proteins, vitamins and steroids.

Kiron et al. [19] examined suitability of two marine algal products as fishmeal substitutes in feeds of Atlantic salmon, common carp, and shrimp. Algal meals were tested at 5 and 10% protein replacement levels for Atlantic salmon and at 25 and 40% for common carp and shrimp. The authors did not find any significant difference in the growth performance at the end of 12-week trial period.

Walker and Berlinsky [20] conducted 84 day trial with juvenile Atlantic cod in which fishmeal was partially replaced by combination of *Nannochloropsis* sp. and *Isochrysis* sp. The authors replaced 0, 15, and 30% of dietary fishmeal protein. The authors found no differences in survival and feed conversion ratios among the treatment and control groups. However, the authors report that those fed the diet with 30% replacement were approaching starvation.

Based on the studies analyzed in this section, all the researchers concluded that fishmeal could not be completely replaced with other protein sources. Table 1 summarizes the findings analyzed in the literature review section.

168 Table 1
169 Summary of Findings from Different Sources

Research	Species Studied	What Components of Diets Have Been Replaced?	What Were the Findings?	Did Researchers Conclude that Fishmeal Could be Completely Replaced?
Aquacop and Cuzon	Shrimp	Up to 20% replacement of fishmeal with soybean meal	The replacement of fishmeal in shrimp feed did not affect growth rates up to 20 percent inclusion	No
Kikuchi	Japanese flounder	Examined the effect of replacing fishmeal with combinations of soybean meal, blood meal, and corn gluten meal.	Up to 45% of fish meal protein can be replaced with SBM in combination with other protein sources in the diet of juvenile Japanese flounder.	No
Ma et al.	Golden pompano	Two 8-wk feeding trials were conducted to examine the effect of replacing fishmeal with poultry by-product meal and soybean meal on growth, feed utilization, body composition performance of juvenile golden pompano.	More than 21% fish meal must be retained in diets for golden pompano when poultry by-product meal or soybean meal is used alone as a fish meal substitute.	No
Smith et al.	Shrimp	Partially Replacing Fishmeal with Meat Meal and Dehulled Lupins	Meat meals can replace about half of the digestible crude protein.	No
Olivera - Novova	Tilapia	Five formulated diets using the microalga spirulina to substitute for 20%, 40%, 60%, 80%, and 100% fishmeal.	Growth rate and protein utilization with 20% and 40% Spirulina were not significantly different from the fishmeal source diet.	No
Tartiel et al.	Tilapia	Studied effect of partial replacement of fishmeal with dried microalgae (<i>Chlorella</i> spp and <i>Scenedesmus</i> spp).	Algae could be utilized in tilapia diets up to 50% instead of the dietary ingredient without adverse effects on fish growth performances.	No
Hanel et al.	Shrimp	Conducted an eleven-week trial to evaluate the growth effect of partial replacement of fishmeal by the microalgae <i>Spirulina platensis</i>	Their results indicated that <i>Spirulina</i> -fed shrimp showed the highest final weight, followed by commercial fish feed, carp feed, and bacteria diet fed shrimp.	No
Kiron et al.	Atlantic Salmon, common carp, and shrimp	Algal meals were tested at 5 and 10% protein replacement levels for Atlantic salmon and at 25 and 40% for common carp and shrimp.	No significant difference was found in the growth performance at the end of 12-week trial period.	No
Walker and Berlinsky	Atlantic cod	Conducted 84 day trial w/ juvenile Atlantic cod in which fishmeal was partially replaced by combination of <i>Nannochloropsis</i> sp. and <i>Isochrysis</i> sp. The authors replaced 0, 15, and 30% of dietary fishmeal protein.	No differences were found in survival and feed conversion ratios among the treatment and control groups. However, those fed the diet with 30% replacement were approaching starvation.	No

3. DATA and INPUT VARIABLES

To apply a hedonic model for valuing whole algae and LEA as an aquaculture feed, the value of the ingredients in whole algae and LEA must be estimated using the implied worth of the ingredients in the feed market. Prices of eighteen different feed meals are used as a vector of independent variables to initiate the hedonic model estimation. From the pool of oilseed products and animal byproducts, the following variables were chosen as they are all feed ration ingredients: soybean meal (high protein), soybean meal (low protein), soybean hulls, whole cottonseed, cottonseed meal, cottonseed hulls, linseed meal, poultry byproduct meal, hydrolyzed feather meal, meat and bone meal, canola meal, sunflower meal, corn gluten meal, prime tallow, yellow grease, bleachable fancy tallow, vegetable-animal blend, and, menhaden fishmeal.

Weekly prices for the 18 feeds from January 2005 to the fourth quarter of 2012 were used in the analysis. Price observations at Fort Worth, Texas, for fourteen commodities were obtained from the Miller Publishing Company publication *Feedstuff*. Weekly prices for menhaden fishmeal and corn gluten meals and weekly prices for canola meal and sunflower meal were available for Chicago, IL and Minneapolis, MN, respectively (due to data unavailability for Fort Worth). Therefore, we incorporated a freight component to calculate the costs to bring these products to Fort Worth, TX. The data for calculating the spread component was obtained through USDA's Agricultural Transportation service and we used the same methodology by assuming shipment of at least 25 cars via unit train and an approximate load per car of 111 short tons [21]. The nutritional compositions of each feed meal represents the independent variable in the hedonic regression., The first step of the model was to carefully select independent variables for the regression which were based on the relative importance of each characteristic for the

aquaculture feed ration, i.e., protein, energy, lipids, minerals, and amino acids.

3.1 Proteins

In contrast to livestock diets, fish diets are very high in protein. The typical diet usually contains at least 50% of protein. Currently, fish meal is a primary source of protein in both fish and shrimp diets. The reason is that in addition to protein, fish meal contains essential amino and fatty acids that usually are not present in tissue from terrestrial plants or animals.

Thus, protein is a vital nutrient for the maintenance and growth of fish. Usually protein is reported as crude protein (CP), which represents approximate total nitrogen multiplied by 6.25 in the diet. Since crude protein is the closest estimation of the percentage of protein in the sample, it is considered to be a candidate in the regression.

3.2 Energy

Fish and shrimp require food to supply the energy that they need for movement and all the other activities. The National Research Council reports Total Digestible Nutrients (TDN) as the most frequently used measurement of energy content. Therefore, TDN was considered to be a candidate in the equation from the energy measurements.

3.3 Lipids

Lipids (fats) are high-energy nutrients that can be used to partially substitute for protein in aquaculture feeds. Usually, lipids supply approximately twice the energy as proteins and carbohydrates. Fish diets contain about 15% of lipids since they also supply essential fatty acids that cannot be synthesized by the organism [22].

Ether Extract (EE) is equivalent to lipids and represents an estimate of total fat or oil content, which is a rich source of energy. Thus, EE was chosen as a candidate in the equation.

3.4 Minerals

Minerals are inorganic elements and they are necessary in the feed diet for normal body functions. However, different from livestock and other animals, fish are able to absorb the majority of their minerals from water, thus requiring a lower amount in their diet. More about adding minerals into the equation will be discussed below.

3.5 Amino Acids

The nutritional value of a particular protein, as described previously, is based on the types and amounts of its amino acids, because proteins are formed by linkages of individual amino acids. Therefore, having high protein content in a particular feed meal does not imply that it will have well balanced amino acids. Among the essential amino acids, lysine and methionine are often the first limiting amino acids that are common in plant type based meals. For example, fish feeds prepared with plant (soybean meal) protein typically are low in methionine and lysine; therefore, extra methionine is usually added to soybean-meal based diets to promote optimal growth and health [23]. Animal proteins are more complete, providing well balanced amino acids which are not available in plant based proteins.

Even though all essential amino acids are required for proper fish nutrition, including all of them in the model would not be practical. Two of the most crucial amino acids were picked according to their deficiency signs in fish and shrimp: methionine (*Met*) and lysine (*Lys*). Deficiency of those amino acids in feed meal causes dorsal/caudal fin erosions, increased

mortality, scoliosis, iordosis, and decreased carcass lipid content. Additionally, methionine deficiency is one cause of lens cataracts [24]. Between these two amino acids, methionine is the most desirable amino acid in fish diets, and it is available only in limited amounts from plant based proteins.

4. METHODOLOGY AND MODEL DEVELOPMENT

4.1 General development

In a hedonic regression, selecting important independent variables and corresponding dependent variables are two distinct tasks. Correctly specified models are important to ensure that there is no endogeneity bias or measurement error in the model. The number of independent variables is also important to avoid over fitting and to allow for sufficient degrees of freedom. The methodology, discussed below, will be considered for the model estimation. For simplicity, consider the simple regression model:

$$y = X\beta + \epsilon \quad (1)$$

where, y is a vector of observations, X is a matrix of known covariates, β is a vector of unknown regression coefficients, and ϵ is a vector of (unobservable random) errors. In this model, the regression coefficients are considered fixed. However, there are cases in which it makes sense to assume that some of these coefficients are random. This is especially the case in the research studied here. In case of feed meal analysis, it is reasonable to assume that the coefficients might change over time. For example, it is logical to think that the average value of protein in the first quarter of 2005 will differ from the average value of protein in the fourth quarter of 2012. Thus a different approach should be implemented to account for those effects. In particular, we employ

266 a linear mixed model to provide this flexibility. Following Laird and Ware [25], the model will
 267 have the following order:

$$268 \quad \mathbf{y}_t = (\beta_1 + b_{1t})\mathbf{x}_{1t} + (\beta_2 + b_{2t})\mathbf{x}_{1t} + \cdots + (\beta_k + b_{kt})\mathbf{x}_{kt} + \boldsymbol{\varepsilon}_t \quad (2)$$

- 269 • $\mathbf{y}_t$ is $n \times 1$ vector of feedmeal prices observed at time t .
- 270 • $\mathbf{x}_{1t}, \mathbf{x}_{2t}, \dots, \mathbf{x}_{kt}$ are vectors of independent variables reflecting the nutritional constituents
 271 of corresponding feedmeals.
- 272 • $\beta_1, \beta_2 \dots \beta_k$ are fixed effects coefficients that do not change over time.
- 273 • $b_{1t}, b_{2t}, \dots b_{kt}$ are random-effect coefficients for time t . Thus, they change over time but
 274 are fixed within the cross section.
- 275 • $\boldsymbol{\varepsilon}_t$ is $n \times 1$ vector of errors for time t .

276 Opening the parenthesis and grouping random effects and fixed effects coefficients along with
 277 covariates together yields:

$$278 \quad \mathbf{y}_t = \beta_1\mathbf{x}_{1t} + \beta_2\mathbf{x}_{2t} + \cdots + \beta_k\mathbf{x}_{kt} + b_{1t}\mathbf{x}_{1t} + b_{2t}\mathbf{x}_{2t} + \cdots + b_{kt}\mathbf{x}_{kt} + \boldsymbol{\varepsilon}_t \quad (3)$$

279 Transferring it into a matrix notation:

$$280 \quad \mathbf{y}_t = \mathbf{X}_t\boldsymbol{\beta} + \mathbf{Z}_t\mathbf{b}_t + \boldsymbol{\varepsilon}_t \quad (4)$$

281 where $\mathbf{X}_t\boldsymbol{\beta}$ is a fixed effect term and $\mathbf{Z}_t\mathbf{b}_t$ is a random effect term. $\mathbf{Z}$ is a possibly full subset of
 282 the $\mathbf{X}$ matrix. In particular, if all the coefficients are assumed to change over time, then $\mathbf{X}$ and $\mathbf{Z}$
 283 are identical.

285 In a linear mixed model, the common assumptions are that $\mathbf{b}_t$ and $\boldsymbol{\varepsilon}_t$, $t = 1, \dots, T$ are
 286 independent.

$$287 \quad \mathbf{b}_t \sim N(\mathbf{0}, \mathbf{D}) \text{ and } \boldsymbol{\varepsilon}_t \sim N_{n_t}(\mathbf{0}, \mathbf{R}_t) \quad (5)$$

288 and from these assumptions it is observed that:

$$289 \quad E(\mathbf{y}_t) = \mathbf{X}_t \boldsymbol{\beta} \quad (6)$$

$$290 \quad Var(\mathbf{y}_t) = \mathbf{Z}_t \mathbf{D} \mathbf{Z}_t' + \mathbf{R}_t \quad (7)$$

291

292 A combined model can be represented as follows:

293

$$294 \quad \begin{pmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \\ \mathbf{y}_3 \\ \vdots \\ \mathbf{y}_T \end{pmatrix} = \begin{pmatrix} \mathbf{X}_1 \\ \mathbf{X}_2 \\ \vdots \\ \mathbf{X}_T \end{pmatrix} \boldsymbol{\beta} + \begin{pmatrix} \mathbf{Z}_1 & \cdots & \mathbf{0} \\ \vdots & \ddots & \vdots \\ \mathbf{0} & \cdots & \mathbf{Z}_T \end{pmatrix} \begin{pmatrix} \mathbf{b}_1 \\ \mathbf{b}_2 \\ \vdots \\ \mathbf{b}_T \end{pmatrix} + \begin{pmatrix} \boldsymbol{\varepsilon}_1 \\ \boldsymbol{\varepsilon}_2 \\ \vdots \\ \boldsymbol{\varepsilon}_T \end{pmatrix} \quad (8)$$

295

296 Laird and Ware [24] suggest a maximum likelihood estimation of the model. In particular, the

297 coefficients of interest can be obtained as follows:

$$298 \quad \hat{\boldsymbol{\beta}} = (\sum_{t=1}^T \mathbf{X}_t' (\mathbf{Z}_t \mathbf{D} \mathbf{Z}_t' + \mathbf{R}_t)^{-1} \mathbf{X}_t)^{-1} \sum_{t=1}^T \mathbf{X}_t' (\mathbf{Z}_t \mathbf{D} \mathbf{Z}_t' + \mathbf{R}_t)^{-1} \mathbf{y}_t \quad (9)$$

299 The random effects, $\mathbf{b}_t$, cannot be directly estimated; however they can be predicted by

300 using the best linear unbiased predictor (BLUP) method. Following Jiang [26], the random

301 effects can be predicted as follows:

$$302 \quad \hat{\mathbf{b}}_t = \mathbf{D} \mathbf{Z}_t' (\mathbf{Z}_t \mathbf{D} \mathbf{Z}_t' + \mathbf{R}_t)^{-1} (\mathbf{y}_t - \mathbf{X}_t \hat{\boldsymbol{\beta}}) \quad (10)$$

303 Since the independent variables do not vary over time in this application (i.e. nutrient

304 content of various feedmeals is assumed to be constant over time), the covariance structure of the

305 random effects will be estimated as independent from each other. In particular, the covariance

between random effects will be assumed to be zero. Following Laird and Ware [25], the equation has the general form:

$$\hat{\mathbf{D}} = T^{-1} \sum_{t=1}^T \mathbf{b}_t \mathbf{b}_t' \quad (11)$$

As described above, *CP* and *EE* are the main source of energy in the diet. Statistical analyses show that including *TDN*, along with *CP* and *EE* makes the *TDN* variable redundant in the equation after *CP* and *TDN* are netted out. Therefore, after controlling for *CP* and *EE* in equation (12), the partial effect of *TDN* on the price of feed meal is zero.

$$E(\text{PriceFM} | CP, EE, TDN, \text{other variables}) = E(\text{PriceFM} | CP, EE, \text{other variables}) \quad (12)$$

As discussed in the previous section, minerals play an important role for the proper feed nutrition and for most of the animals, they are a necessary component in the diet. However, in the case of aquaculture, if water quality is good (depending on water salinity and acidity as well as the amount of dissolved calcium and magnesium in the water), fish and shrimp can absorb minerals from the water, which negates the need for them in the diet. Even though minerals in feed meals are important for general consumption, if we truly wish to represent the model for aquaculture, including minerals will yield no substantial improvement. Thus, minerals have been excluded from the regression.

Choosing the appropriate essential amino acids in the equation is the most important part to truly capture the value of a particular feed meal for aquaculture. As described in the previous section, high protein in the feed meal does not imply well balanced amino acids, thus, both *CP* and particular amino acids must be present in the equation. Including all essential amino acids in the regression is impractical, because it would overfit the model and yield high multicollinearity

among the independent variables. Since, methionine and lysine are considered the most critical amino acids in the diet and are present in very limited amounts in plant based feed meals (especially methionine), these two variables are included in the regression. Moreover, a quadratic function of methionine (Met^2) was added in the model to capture increasing or decreasing the marginal effect of this random variable.

The final model is divided by fixed effects and random effects coefficients represented by X and Z, respectively.

$$X_t = Constant, CP, EE, Met, Met^2, Lys \text{ and}$$

$$Z_t = Constant, CP, EE, Met, Lys \quad (13)$$

where the price of feedmeal ($Price_{FM}$) is determined by the constant, content of crude protein (CP), either extract/fat (EE), methionine (Met), a quadratic function for methionine (Met^2), and lysine (Lys). The stochastic error term is represented by the symbol ε in the equation. The prices of eighteen feed meals represent the set of dependent variables for the model, while the selected ingredients (CP, EE, Met, Met^2 , and Lys) of feed meals were used as covariates in the regression. The weekly data from January 2005 to December 2012 were aggregated and transformed to a quarterly basis. Therefore, the aggregated data represents a total of thirty-two time periods from the first quarter of 2005 to the fourth quarter of 2012.

5. RESULTS

The linear mixed model was run for thirty-two time periods for eighteen commodities and the coefficients along with corresponding standard errors were reported. The results of the hedonic regression fixed effects parameter estimates are represented in Table 2. The results indicate that all variables are significant at 99% confidence level.

Table 2
Linear Mixed Model Regression Results of the
Fixed Effects for Periods Q1, 2005 through Q4, 2012*

	Coefficient Estimates
Constant	106.66 (11.47)
CP	2.86 (.31)
EE	4.80 (.39)
Met	-198.41 (26.36)
Met ²	218.39 (8.96)
Lys	20.19 (3.64)

* Standard errors are in parentheses

Standard deviations of random effects coefficients parameters along with standard errors and 95% confidence intervals are reported in Table 3. The model initially was run also with allowing *Lys* to vary over time, however the standard deviation of the variable was literally zero and including *Lys* did not improve the overall Chi-squared score. The table shows that, given the 95% confidence interval for standard deviations, it would seem that the random slopes are statistically different from zero. The likelihood ratio test was used to verify this fact and the result showed that the model with random slopes versus random intercept only had near-zero

significance level and favored the model that allowed for a random time specific regression line over the model that allowed only for a time specific shift. A likelihood-ratio test comparing the model with one-level ordinary linear regression is highly significant. The value of 746.32, distributed Chi-squared with four degrees of freedom, results in a p-value of less than 0.001.

Table 3
Random-Effects Parameters Estimation of Constant, CP, EE, and Met.**

	Estimate	[95% Confidence Interval]	
Constant	29.75 (9.07)	16.36	54.08
CP	1.07 (.22)	0.72	1.61
EE	2.18 (.28)	1.69	2.82
Met	81.65 (12.33)	60.72	109.79

**LR. Test vs. Linear regression: Chi square (4) = 746.32 Prob > Chi square = 0.000
Standard errors are in parentheses

Accounting for both methionine and the quadratic function of methionine in the regression has some interesting results. Since the coefficient of *Met* remained negative and the coefficient of *Met*² was always positive, the quadratic has a parabolic shape. Over relevant ranges for aquaculture, high methionine content makes a substantial contribution to feed ingredient value.

5.1. Hedonic Price Estimations for Whole Algae and LEA.

Random effects were predicted for thirty-two time periods using the BLUP method. Once the feed meal characteristics that have a significant impact on the feed meal prices were identified, the predicted coefficients were used in conjunction with the corresponding nutrient

content of whole algae to determine the value of the product. The implied value of whole algae was calculated at each time interval from the first quarter of 2005 through the fourth quarter of 2012 based on the quantities of CP, EE, Met, and Lys in the algae sample.

Two different species of whole algae were used for the determination of the value of whole algae as an aquatic specie feed: *Chlorella pyrenoidosa*, and *Nannochloris oculata*, flocculated expanded collets. With regards to LEA, *Nannochloris oculata*, flocculated expanded collets, hexane extracted meal was used for the analysis. Nutritional composition of whole *Chlorella pyrenoidosa* was obtained from Becker [27]. Nutritional compositions of whole *Nannochloris oculata* and *Nannochloris oculata* LEA are coming from authors' original measurements that is also available in Bryant et al. [28]. Nutritional components of other feedmeals were obtained from Midland [29] and Tacon, Metian , and Hasan [30]. Table 4 shows the chemical compositions of whole algae and LEA species and comparison with soybean meal and menhaden fishmeal.

Table 4
Chemical Composition of Whole Algae Samples, LEA, Soybean Meal, and Menhaden Fishmeal

Description	Whole <i>Chlorella pyrenoidosa</i>	Whole <i>Nannochloris oculata</i>	<i>Nannochloris oculata</i> LEA (drum-dried, ethanol extracted meal)	Soybean Meal	Menhaden Fishmeal
CP	57.00%	26.66%	34.20%	54.00%	66.00%
EE	2.00%	1.83%	<0.2%	1.10%	10.59%
Met	1.03%	0.33%	0.30%	0.68%	1.88%
Lys	4.50%	1.43%	1.76%	3.08%	5.10%

Source: Becker (1994), Bryant et al. (2012), Tacon, Metian, and Hasan (2009)

It is noted that plant based meals lack methionine content, whereas menhaden fishmeal contains at least twice more of that amino acid than any plant based meal. However, when comparing whole *Chlorella pyrenoidosa* with soybean meal, the whole algae generally dominates soybean meal in any content component. Whole *Chlorella pyrenoidosa* shows much more balanced

amino acid profiles than soybean meal. However, nutritional contents of whole *Nannochloris oculata* and *Nannochloris oculata* LEA are significantly lower than the contents of whole *Chlorella pyrenoidosa* and soybean meal. Despite low EE compositions, CP, Met, and Lys contents are also significantly lower. Comparing whole algae versus LEA, figure 1 shows the hedonic prices of algae species after plugging the estimated coefficients into the corresponding percentage content of whole algae and LEA.

As represented in the graph, the hedonic prices of algae species exhibit significant trends and are closely related. Whole *Chlorella pyrenoidosa* is initially priced at \$210 per short ton, which also happens to be the minimum price in the sample period. The peak is reached in the third quarter of 2012, where the whole *Chlorella pyrenoidosa* reaches the maximum price of \$583 per short ton¹.

As pointed out earlier, both whole *Nannochloris oculata* and *Nannochloris oculata* LEA present significantly lower nutrient contents when compared to whole *Chlorella pyrenoidosa* and soybean meal. Therefore, the estimated hedonic prices were significantly lower than the values of whole *Chlorella pyrenoidosa*. Whole *Nannochloris oculata* is initially priced at \$102 per short ton and exhibits a significant growth over the sample period. The peak is reached in the third quarter of 2012, where the whole *Nannochloris oculata* reaches the maximum value of \$290 per short ton. With regards to *Nannochloris oculata* LEA, the minimum price is observed in the first quarter of 2005 (\$126 per short ton) and the maximum value is observed in the third quarter of 2012 as well (reaching \$319 per short ton).

¹ There can be algae-specific qualities that might influence the prices but are not reflected in hedonic methodology. This could either understate or overstate the true value of the feedstock. For example, if the digestibility of a specific algae meal in fish is low, this would be an algae specific shifter and the true price will be lower than the price predicted by the hedonic methodology.

Comparing the values of whole algae to the values of LEA has interesting implications. The prices of whole *Nannochloris oculata* were compared to the values of *Nannochloris oculata* LEA because they are the same species and are based on the same growth conditions. *Nannochloris oculata* LEA has higher concentration of *CP* and lysine and has lower content of *EE* when compared to whole *Nannochloris oculata*. *Nannochloris oculata* LEA is also expected to have a higher concentration of *Met*, however the analytical measurement did not detect an increase in *Met* content after lipid extraction. Generally, LEA is expected to have a higher concentration of *Met* than whole algae. The results showed that the higher concentrations of lipids did not outweigh the lower contents of *CP* and *Lys* content and therefore the nutritional value of whole *Nannochloris oculata* is slightly lower when compared to *Nannochloris oculata* LEA. In particular, the range of price difference between the two is \$8 to \$38 per short ton. Even though the whole *Chlorella pyrenoidosa* is priced higher than *Nannochloris oculata* LEA, it is impractical to compare these values as they are not the same species. Although it was expected that *Chlorella pyrenoidosa* LEA would have the higher nutritional value than whole *Chlorella pyrenoidosa*, it is impossible to determine the magnitude of the difference unless the actual values are compared.

The hedonic prices of whole *Chlorella pyrenoidosa* and *Nannochloris oculata* LEA were compared to the actual historic prices for different feed meals and the comparisons are reported in the subsequent sections.

5.2. Whole *Chlorella pyrenoidosa* and *Nannochloris oculata* LEA vs. soybean meal

Figure 2 demonstrates that, whole *Chlorella pyrenoidosa* is priced higher in all periods than soybean meal. This result was expected, since whole *Chlorella pyrenoidosa* dominates soybean meal in terms of nutritional content for all important nutrients. Whole *Chlorella pyrenoidosa* has higher *CP* content, higher lipids and most importantly a better balanced amino acid profile. However, since they appear to be close substitutes, the movements of the prices are very similar. Both of the commodities exhibit the same trend and changes in the market values of the nutrients have similar impact on the prices of both feed meals.

On the other hand, soybean meal is priced higher in all periods than *Nannochloris oculata* LEA. This result was expected, because nutritional composition of *Nannochloris oculata* LEA is significantly lower than that of soybean meal. The difference is noticeable especially in terms of *CP* and *Lys* contents. Moreover, *Met* content of soybean meal is twice as high as *Nannochloris oculata* LEA. Nevertheless, price movements of both feed meals are similar and they both exhibit a similar trend².

² Since *Nannochloris oculata* LEA has lower nutritional value than soybean meal, a reader might be interested to know what the approximate cost of supplementing *Nannochloris oculata* LEA with synthetic amino acids would be to make the algae meal comparable with soybean meal. We calculated the difference in each nutritional component and applied the values in our model. The range of premium across the thirty two time periods were between \$90 and \$152 per short ton.

5.3. Whole *Chlorella pyrenoidosa* and *Nannochloris oculata* LEA vs. menhaden fishmeal

The comparison of whole *Chlorella pyrenoidosa* and menhaden fishmeal indicates that the latter is priced higher in all time periods (Figure 3). Since menhaden fishmeal is the main feed ingredient in aquaculture diets, the result was consistent with expectations. The reason can be explained simply: the nutritional quality of fishmeal is higher than any plant based meal and it has the most well balanced amino acid profile as well.

Initially the price difference between these two commodities is approximately \$372. Over time, however, the price difference becomes more apparent. In 2010, the price of fishmeal skyrocketed and reached over \$1490, while the hedonic price of whole *Chlorella pyrenoidosa* remained relatively balanced. In particular, the price difference between fishmeal and whole *Chlorella pyrenoidosa* approaches \$969 by the third quarter of 2010.

The price movement deviation between fishmeal and two algae species are noticeable starting from the 3rd quarter of 2009. At least two arguments can be presented to support the fact. Increased demand on aquaculture products by consumers accelerated the demand for fishmeal by the producers. Later, an earthquake in Chile in late February, 2010 further tightened suppliers as Chile is the second largest fishmeal producer. By that time prices of fishmeal skyrocketed and reached record high. This fact further strengthens the argument that substitutability between fishmeal and plant based meals are limited.

5.4. Whole *Chlorella pyrenoidosa* and *Nannochloris oculata* LEA vs. corn gluten meal

The price movement between whole *Chlorella pyrenoidosa* and corn gluten meal is very similar (Figure 4). The difference is very small and at some point the prices are almost the same.

However, corn gluten meal is priced higher in most of the time periods. Corn gluten meal has a higher content of *CP*, *Met*, and *EE*, while whole *Chlorella pyrenoidosa* has a higher content of *Lys*. As the graph demonstrates, the feedmeals are very close substitutes and the price differences are very small. The price difference becomes large in the third and fourth quarter of 2012, which can be attributed to both an appreciation of *Met* value in the feedmeals and increased corn price presented in the late 2012.

On the other hand, price competition between *Nannochloris oculata* LEA and corn gluten meal is not as tight as it was in the case of whole *Chlorella pyrenoidosa*. *Nannochloris oculata* LEA has significantly lower contents of nutrient components when compared to corn gluten meal. In particular, *CP* and *Met* composition of latter is three times higher than that of former. These differences are the main reasons for corn gluten meal being priced higher *Nannochloris oculata* LEA. Price movements are similar, however.

5.5. Whole *Chlorella pyrenoidosa* and *Nannochloris oculata* LEA vs. meat and bone meal

Whole *Chlorella pyrenoidosa* is priced higher than meat and bone meal in all time periods (Figure 5). Whole *Chlorella pyrenoidosa* has better nutritional quality in terms of *CP* and amino acid profile. Especially the difference can be noticed in *CP* content. Meat and bone meal has approximately 56% of *CP* content, whereas whole *Chlorella pyrenoidosa* has about 57%. Although the difference in *CP* content between the two feedmeals is negligible, the amino acid profile of whole *Chlorella pyrenoidosa* is significantly higher when compared to meat and bone meals. Conversely, meat and bone meal has higher lipid content which is about 10%. However the better amino acid profile of whole *Chlorella pyrenoidosa* outweighs the relatively low content of lipids and therefore the value is higher than the value of meat and bone meal in all

time periods. The price movements are very similar and they both have the similar trend.

Different from the above, meat and bone meal is priced higher than *Nannochloris oculata* LEA in all time periods. Nutritional quality of meat and bone meal is superior in terms of *CP*, *EE*, *Met*, and *Lys* contents. Meat and bone meal has at least twice as high *CP*, *Met*, and *Lys* than *Nannochloris oculata* LEA. Moreover, meat and bone meal has ten times higher lipid content than the algae meal.

5.6. Whole *Chlorella pyrenoidosa* and *Nannochloris oculata* LEA vs. hydrolyzed feather meal

Prices of whole *Chlorella pyrenoidosa* and hydrolyzed feather meal are generally comparable (Figure 6). Approximately half of the time, whole *Chlorella pyrenoidosa* has a higher price than hydrolyzed feather meal. The two prices almost converge at three points in the first quarter of 2010 and in the second and third quarters of 2011. This result was expected, as the nutritional qualities of the two commodities are very similar. Hydrolyzed feather meal has higher content of *CP* and ether extract, whereas whole *Chlorella pyrenoidosa* has better balanced amino acid profile, with higher content of both *Met* and *Lys*.

On the other hand, hydrolyzed feather meal is priced higher than *Nannochloris oculata* LEA in all time periods. Nutritional quality of the former is much superior to that of the latter. The difference is noticeable especially in *CP* content. Hydrolyzed feather meal has about three times higher *CP* content than *Nannochloris oculata* LEA.

529

6. SCENARIO ANALYSIS

530 This section focuses on estimating the values of two hypothetical algae meal samples
531 different from the LEA presented in the results section. Once algae meal enters the feed market,
532 it would seem reasonable that manufacturers will optimize their production process to make their
533 feedstuff as competitive as other meals available in the market. Thus, the algae meal would more
534 likely have better nutritional qualities than those presented in the previous section. As it is
535 difficult to obtain published data on higher quality algae meals, we conducted a scenario analysis
536 and run the model with two hypothetical algae meals. For the first hypothetical meal, we took the
537 average chemical compositions of all plant based meals analyzed in the study (i.e. soybean meal,
538 canola meal, cottonseed meal, linseed meal, etc.). With this approach we assume that once algae
539 meal enters the market, it will mainly compete among plant based meals to partially replace
540 fishmeal. For the second hypothetical meal, we altered only methionine and lysine contents and
541 set at the minimum levels required for shrimp nutrition. The minimum requirement levels were
542 obtained from Millanema *et al.* [31, 32]. Even though the minimum requirements are set for
543 shrimp, we assume that it holds for other species as well (i.e. tilapia, salmon). Chemical
544 compositions of two hypothetical algae meals are summarized in table 5. As shown in the table,
545 the values are higher in all nutritional components when compared to *Nannochloris oculata*
546 LEA.

547

Table 5

Chemical Composition of two Hypothetical Algae Meal Samples

Description	Algae Meal 1	Algae Meal 2
CP	45.10%	45.10%
EE	2.59%	2.59%
Met	0.76%	0.90%
Lys	1.88%	2.10%

The hypothetical algae meal sample values were estimated for thirty-two time periods and the results are presented in figure 7. The price movements of both algae meals are very similar. As expected, hypothetical algae meal sample that has the minimum methionine and lysine recommended levels are priced higher than algae meal that is weighted based on average chemical compositions of plant based meals. The price difference is small at the beginning and the minimum is observed in the first quarter of 2005 where the price difference is about \$11 per short ton. However as the time passes and animal based meals become more expensive, the values of methionine and lysine increase as well. As a result, the peak is observed in the third quarter of 2010 where the price difference between the meals reaches about \$49 per short ton. The highest prices for both species are observed in the third quarter of 2012, where algae meal 1 and algae meal 2 reach about \$426 and \$465 per short ton, respectively. With regards to the comparison with *Nannochloris oculata* LEA, the mean price difference between algae meal 1 and *Nannochloris oculata* was \$65 per short and the mean price difference between algae meal 2 and *Nannochloris oculata* LEA was \$95 per short ton.

7. CONCLUSION

Aquaculture has the highest rate growth among all other sectors of the food industry.

Fishmeal is a vital component in the feed diet and since the last decade the world production of fishmeal has been stable. The growth of aquaculture and relatively stable fishmeal production has caused a substantial increase in fishmeal prices. Aquaculture has been seeking alternatives for fishmeal replacement and extensive research has been conducted by various individuals and institutions for the last three decades.

The purpose of this research was to utilize the existing feed meals in the market to calculate the value of whole algae and lipid extracted algae based on its nutritional value for aquaculture. Estimated prices of whole and lipid extracted algae in this research can be used in feasibility studies to calculate the realistic potential profitability of algae farms.

The results indicated that, for thirty-two time periods, the values of whole *Chlorella pyrenoidosa* and *Nannochloris oculata* LEA were between \$210 to \$583 and \$126 to \$319 per short ton, respectively. The results are slightly different from the results found by Bryant et al. [27], where the authors estimated that selling LEA as livestock feed ingredients has prices ranging \$100 to \$225 per short ton based on its livestock market contribution. The range of price differences between menhaden fish meal and whole *Nannochloris oculata* was \$363 to \$969 per short ton over the sample period. The range of price difference between menhaden fishmeal and *Nannochloris oculata* LEA was \$456 to \$1258 over the sample period. Whole *Chlorella pyrenoidosa* was priced higher than soybean meal in all periods. The range of price differences between whole *Chlorella pyrenoidosa* and soybean meal was \$26 to \$170 per short ton over the sample period. On the other hand, soybean meal was priced higher than *Nannochloris oculata* LEA in all time periods and the range of price difference was between \$38 to \$226 per short ton.

Fully substituting a fishmeal with a plant based feed meal, including algae, is virtually impossible. As suggested from the literature, total replacement of fishmeal by algal meal generally shows poor growth responses.

Nutritional quality of whole algae and LEA depends on the type of species used for the analysis. For example, whole *Chlorella pyrenoidosa* has the potential to compete and fully substitute for soybean meal and other plant based meals in aquaculture diets (even though the share of plant based meals in aquaculture is approximately 10-20%). Compared to soybean meal, whole *Chlorella pyrenoidosa* has a higher crude protein and lipid content which are both necessary in the diet and more importantly have a better balanced amino acid profile, making algae an attractive choice among plant based meals. On the other hand, the nutritional value of both whole *Nannochloris oculata* and *Nannochloris oculata* LEA in aquaculture is limited. When comparing whole algae versus the LEA, the results indicated that *Nannochloris oculata* LEA was priced higher than whole *Nannochloris oculata* in all time periods. The range of price differences between the two was \$9 to \$38 per short ton.

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Figures

Fig. 1. Price comparison of two different whole algae and LEA.

Fig. 2. Value comparison of whole *Chlorella pyrenoidosa*, *Nannochloris oculata* LEA and Soybean meal (high protein).

Fig. 3. Comparison of whole *Chlorella pyrenoidosa* value, *Nannochloris oculata* LEA value and menhaden fishmeal price.

Fig. 4. Comparison of whole *Chlorella pyrenoidosa* value, *Nannochloris oculata* LEA value, and the price of corn gluten meal.

Fig. 5. Comparison of whole *Chlorella pyrenoidosa* value, *Nannochloris oculata* LEA value, and the price of meat and bone meal.

Fig. 6. Comparison of whole *Chlorella pyrenoidosa* value, *NO flocc* LEA value, and the price of hydrolyzed feather meal.

Fig. 7. Comparison of two hypothetical algae meal sample values.