

## DYNAMIC STOCHASTIC ADAPTIVE BIOECONOMIC MODEL OF OFFSHORE BLUEFIN TUNA AQUACULTURE

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□ *This research presents a bioeconomic framework for assessing the economic feasibility of an offshore bluefin tuna aquaculture operation by developing a dynamic stochastic adaptive bioeconomic model of such an offshore enterprise. The bioeconomic model incorporates the biological constraints of the species, the interaction of relevant economic parameters and constraints, and stochastic sources of risk to solve for the profit maximizing behavior of a farmed bluefin tuna producer. The model identifies the optimal harvest schedule for an offshore bluefin tuna farming facility that maximizes the net present value of the operation under a variety of economic, biological and regulatory conditions. Such a model is relevant given the growing prevalence of bluefin tuna farming worldwide, the present lack of studies formally examining the economics of this form of production, and the uncertainty surrounding the economic feasibility and sustainability of this form of production.*

**Keywords** aquaculture, bioeconomics, bluefin tuna, dynamic models, stochasticity

### INTRODUCTION

Capture-based bluefin tuna aquaculture has transformed the bluefin tuna industry over the past 15 years, altering how bluefin tuna is supplied to the market. As it is currently practiced, this form of production involves the capture, penning, and fattening of wild-caught bluefin tuna for a period of time to increase their weight and fat content before slaughter. While researchers in Japan have closed the life cycle for Pacific bluefin tuna, this form of production has not yet been implemented on a commercial scale to date (Sawada et al., 2005). Recently, Australian and European researchers successfully created artificial breeding regimes for Southern bluefin tuna and Atlantic bluefin tuna, respectively (Clean Seas Tuna Limited, 2008a, 2008b). This is a major step towards the closed-cycle

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breeding of bluefin tuna for farming purposes; however, until the closed-cycle breeding of bluefin tuna is commercially implemented, the industry will remain reliant upon wild bluefin tuna populations.

Bluefin tuna farming is an interesting and complex form of production; however, to date there are very few published studies that empirically examine this practice. This research is a first step in filling this gap in the literature by establishing a bioeconomic framework for modeling the economics of farmed bluefin tuna production.

Specifically, this research identifies the optimal harvest schedule for an offshore bluefin tuna farming facility that maximizes the net present value of the operation under a variety of economic, biological and regulatory conditions. Further, this research explicitly incorporates stochasticity into the model in order to analyze how the presence of risk alters the optimal harvest schedule for a producer. Very few studies have incorporated risk into the economic analysis of offshore aquaculture (Brown et al., 2002; Kam et al., 2003; Posadas & Bridger, 2003; Jin et al., 2005) and none have incorporated the role of risk in the analysis of the economics of farmed bluefin tuna production.

### BRIEF BACKGROUND ON BLUEFIN TUNA FARMING

Bluefin tuna is a highly migratory species that inhabits a variety of oceans throughout the world. There are three species of bluefin tuna: Atlantic bluefin tuna (*Thunnus thynnus*), Pacific bluefin tuna (*Thunnus orientalis*), and Southern bluefin tuna (*Thunnus maccoyii*), all of which are farmed at present. Many countries are involved in this practice including: Australia, Japan, Mexico and Mediterranean countries including but not limited to, Croatia, Spain, Malta, and Turkey. Due to its high quality flesh and fat content, bluefin tuna is a prized commodity in Japan's Tsukiji market, the primary market for *sashimi* grade tunas. In Japan, bluefin tuna is typically consumed raw as *sashimi* or with rice as *sushi*. On a per pound basis, bluefin tuna is one of the most valuable species in the world (Deere, 2000). In 2001, one 202 kilogram bluefin tuna caught off the northern coast of Oma, Japan sold at the Tsukiji market for 862 USD/kg (116.06 JPY/USD) setting the all time record for price per kilogram that still stands today (OPRT, 2008). More recently in January 2009, a 128 kilogram wild Pacific bluefin tuna that was also caught off the northern coast of Oma, Japan sold in the Tsukiji market for 807 USD/kg (93.22 JPY/USD) (Yamaguchi, 2009). One important characteristic of bluefin tuna is how it is priced in the market. In contrast to most seafood species, the price of a bluefin tuna is determined on an individual basis, where each fish is graded on various characteristics including freshness, fat content, color and shape (Carroll et al., 2001). Quality is of utmost importance with regard to the Japanese market and as such, quality is a very important

distinguishing factor in determining the price of a bluefin tuna. A key quality characteristic influencing the price of an individual bluefin tuna is the fat content of the fish. All things being equal, a fish with a higher fat content will receive a higher price in the market (Carroll et al., 2001). Thus, the incentives to farm bluefin tuna relate back to the manner in which it is priced in the market. The market rewards those who employ methods of production that either maintain or enhance a fish's underlying quality characteristics. This form of production can transform leaner fish that, when initially caught, are not as desirable or valuable in the market, into fatter fish that can command higher prices. One major economic question stemming from this form of production is: how long should a producer retain and feed a given quantity of wild-caught bluefin tuna before harvesting and selling those fish? That is to say, what is the optimal harvest schedule for a producer looking to maximize profits over a farming season?

## **MATERIALS AND METHODS**

The bioeconomic model is formulated as a finite horizon model as opposed to an infinite horizon model due to the biological and regulatory constraints associated with bluefin tuna farming as it is currently practiced. At present, the bluefin tuna farming industry is solely reliant upon wild-caught bluefin tuna for stocking in the growout pens. Since there is no hatchery-based production of bluefin tuna seed stock, the industry is constrained as to when and where it can obtain fish for stocking and growout. This constraint is both biological and regulatory in nature. Since bluefin tuna are highly migratory, the fish may not be physically accessible when they are demanded by the farm for stocking purposes. Also, the fish may be too small for legal capture and/or the fishery may be closed at a particular point in the season, thereby making the fish unavailable. Finally, depending on the location of the farming enterprise, bluefin tuna farming may not extend year-round if the water temperatures fall below a critical level. While larger bluefin tuna are typically able to thermoregulate their body temperatures, smaller tunas may be unable to tolerate cold water temperatures (10 degrees Celsius or less) for an extended period of time (Magnusson et al., 1994; Block et al., 2001). Thus, for these reasons, the harvesting and restocking decision of a bluefin tuna farmer is constrained, negating the applicability of an infinite horizon model. However, if the bluefin tuna farming industry were to transition to a closed-cycle production system, then such a formulation would be relevant.

## INCORPORATING STOCHASTICITY INTO THE BIOECONOMIC FRAMEWORK

In explicitly modeling the stochastic nature of production, this model incorporates the risks associated with the offshore production of bluefin tuna, including biological, technical, economic, and regulatory sources of risk. This modeling approach is especially useful given the uncertainty surrounding the values and behavior of certain parameters associated with bluefin tuna farming. In many cases, specific knowledge of growth rates, mortality rates, input costs and output price are unknown. However, such parameters can be specified as stochastic within the model in order to capture the potential effect of these stochastic variables on the optimal harvest schedule and overall economic performance of the operation.

The model is a useful tool for those in the farming industry as well as investors and regulatory agencies. The model can be used to quantify the economic benefits and tradeoffs associated with the farming of bluefin tuna, in particular in situations where key variables are uncertain or are assumed to be stochastic. Furthermore, the model can be used to analyze how various assumptions regarding growth rates, water temperatures, prices or costs affect the optimal harvest decisions and the overall economic performance of an operation.

## DISTINCTION FROM PREVIOUS RESEARCH

This research differs from previous studies in the field of aquaculture research with regard to the treatment of stochasticity within the model. In general, many economic optimization models solve the entire production or planning horizon once. That is to say, the optimal harvest solution is solved across all periods given the assumptions and parameters that are specified *ex ante*. This modeling framework implicitly assumes that these parameters will not deviate from their *ex ante* values over the course of the production horizon, which may or may not be true. Employing Monte Carlo analysis is an improvement over models which are based on deterministic, fixed-point estimates of key parameters because they allow for the calculation of multiple fixed-point estimates which are chosen to hold over a production horizon.

In contrast to models which rely on deterministic fixed point estimates which implicitly assume that the farmer would not deviate from the optimal harvest schedule in-season, the dynamic stochastic adaptive bioeconomic model developed here explicitly incorporates the adaptive behavior of the firm over the course of the operating horizon. In each period, the entire operating horizon is resolved iteratively from  $t = t_1$  to  $t = T$ . Thus, rather than calculating and relying on one fixed optimal harvest schedule for the entire operating horizon, the model recalculates

a new optimal harvest schedule each period as new information regarding the behavior of stochastically specified parameters changes over time. Thus, in the first period, expectations for stochastic parameter values are formed and are used to solve for the initial optimal harvest schedule, and the first optimal solution is executed. However, at the end of the first period, the farmer observes the actual values of the stochastic parameters, which may deviate from the expected values that were used to solve the initial optimal harvest schedule. Using this new information, the farmer updates the expectation of next period's stochastic parameters and recalculates a new optimal harvest schedule for the remaining periods in the operating horizon, given that a decision has already been made for the first period. In this manner, the farmer makes a decision period by period as new information is observed. The farmer is not constrained to stick to an optimal harvest schedule for the duration of the operating horizon. Rather, the farmer is able to re-solve for the optimal harvest schedule for the remainder of the operating horizon each period, in an adaptive manner. Hence, this model is dynamic, in that it solves for the optimal harvest schedule over time, it is stochastic since it allows for the specification of stochastic parameters, and it is adaptive in that it allows a farmer to adapt to changing parameters in-season.

Such a model allows for a more realistic representation of risk and a farmer's response to risk throughout the production horizon. Compared to a non-adaptive model that solves for the optimal harvest schedule for the entire operating horizon once, the adaptive model's performance is typically higher (the NPV of the adaptive model equals or exceeds the NPV for a non-adaptive model) when operating under stochastic situations where parameter values change each period. The adaptive model performs better since it can alter the optimal harvest schedule in-season. This is in contrast to a non-adaptive model, which is limited to a single optimal harvest schedule based on *ex ante* estimates despite the fact that the values of those parameters change in-season due to the stochastic nature of the operating environment.

### FORMAL DEVELOPMENT OF THE BIOECONOMIC MODEL

The objective function for a risk neutral profit maximizing offshore bluefin tuna aquaculture producer is defined as follows:

$$\text{Max } \pi_{H_t} = \sum_t^T \left\{ P_t(W_t, H_t, G_{i,t}) W_t H_t - C_{HC} H_t - C_{VC_t} N_t \right\} \cdot \frac{1}{(1+r)^t} - A_0 \quad (1)$$

Subject to:

$$\begin{aligned}
 P_t &= P_t(W_t, H_t, G_{it}) \\
 W_t &= f(FCR_t, FR_t(WT_t)) \\
 G_{i,t} &= G_{t-1} + \left( \frac{W_t - W_{t-1}}{W_T - W_{(0)}} \right) \cdot (G_T - G_{(0)}) \\
 N_t &= N_{t-1}(1 - M_{t-1}) - H_{t-1} \\
 N_t, H_t &\geq 0 \\
 N(0) &= N_0
 \end{aligned}$$

where:

$P_t$  = Price per kilogram of an individual bluefin tuna, as a function of the weight, grade of the fish ( $G_{i,t}$ ) and harvest quantity of fish at time  $t$ .

$W_t$  = Weight of a individual bluefin tuna at time  $t$  measured in kilograms, as a function of the feed conversion ratio and the daily feeding rate, which itself is a function of water temperature.

$G_{i,t}$  = Grade of the fish at time  $t$ , where  $i$  = Color, Freshness, Fat and Shape.

$H_t$  = Harvest quantity of bluefin tuna at time  $t$ .  
This is the control variable of the farmer.

$N_t$  = Number of bluefin at time  $t$ .

$C_{HC}$  = Harvesting costs (\$/kg).

$C_{VC_t}$  = Aggregation of variable costs at time  $t$  (\$/kg).

$FCR_t$  = Feed Conversion Ratio at time  $t$ , which can be time invariant or a function of time.

$FR_t$  = Feeding Rate at time  $t$ , which is a function of the water temperature ( $WT$ ) at time  $t$ .

$A_0$  = Total Acquisition Costs associated with acquiring bluefin tuna for farming.

$M_t$  = Natural Mortality rate at time  $t$ , which can be time invariant or a function of time.

$N_0$  = Initial starting number of bluefin tuna.

$r$  = Discount rate (weekly).

The optimal harvest schedule is solved for by maximizing the above objective function numerically through the use of a non-linear constrained

optimization (Sequential Quadratic Programming) algorithm found within Matlab's Optimization toolbox. The time step for the model is weekly.

## DISCUSSION OF SUB-MODEL COMPONENTS

The following sections explain each component of the bioeconomic model for an offshore bluefin tuna farming operation in greater detail.

### BIOLOGICAL SUB-MODEL

#### Growth and Weight Function Component

Based on the research of Kam et al. (2003) on farmed Atlantic bluefin tuna in Croatia, a relationship between water temperature and daily feeding rate was estimated.

$$FR_t = 1.29 WT_t - 20.29 \quad (2)$$

$$t\text{-statistics} : (12.73)(-9.99)R^2 = .97$$

where

$$0.1\% \leq FR_t \leq 11\%$$

$FR_t$  = Feed consumed daily as a percentage of the body weight at time  $t$ .

$WT_t$  = Water temperature measured in degrees Celsius.

The daily feeding rate provides an estimate of feed consumed by an individual bluefin tuna daily, expressed as a percentage of the body weight of the fish at time  $t$ . The bioeconomic model is weekly; however, the time step of Equation (2) is daily. To address this discrepancy, it is assumed that the weekly water temperatures ( $WT_t$ ) represent the average daily water temperature for the week. It is in this way that weekly data is used to approximate daily values for these parameters.

Daily feeding rates ( $FR_t$ ) are constrained to be less than or equal to 11%, and greater than or equal to 0.1%. This prevents the model from feeding fish in excess of their observed biological ability and also prevents negative feeding and negative growth of the fish if  $FR_t$  is allowed to be less than zero (Katavic et al., 2003a). Currently the industry relies on the feeding of whole fish (fresh or previously frozen) to fatten the tuna over time. Types of small pelagic fish include, but are not limited to, mackerel, herring, sardines, and sprats. Farmed bluefin tuna are typically fed until satiation once or twice daily, 6 days a week. In some countries, the fish are given a day off to minimize potential damage to their livers due to overfeeding (Zertuche-Gonzalez et al., 2008).

FCR can be specified as either a function of time or time invariant. In the literature, FCR is commonly reported as time invariant; therefore, FCR will be assumed to be a constant parameter over the course of the farming season (Ikeda, 2003; Katavic et al., 2003b; Ottolenghi et al., 2004; Aguado-Gimenez & Garcia-Garcia, 2005b).

Growth in this model is assumed to be density independent. All farmed bluefin tuna are assumed to be of the same age and size cohort, and growth will be assumed to be homogeneous throughout the production process. Therefore the bioeconomic model captures the changes in the weight and harvest schedule for the representative or average fish. Growth over a week of feeding is modeled in a manner that captures the influences of water temperature, feeding rate and FCR on the increase in weight of a fish each period.

$$W_{t+1} = W_t + \frac{(1.29WT_t - 20.29)W_t \cdot 6}{FCR} \quad (3)$$

### Water Temperature Regime

In order to solve Equations (2) and (3), a water temperature regime must be specified. For the model presented here, water temperatures are based on an average of 5 years of observations from the NOAA National Data Buoy Center database<sup>1</sup> (Fig. 1). Season length is governed

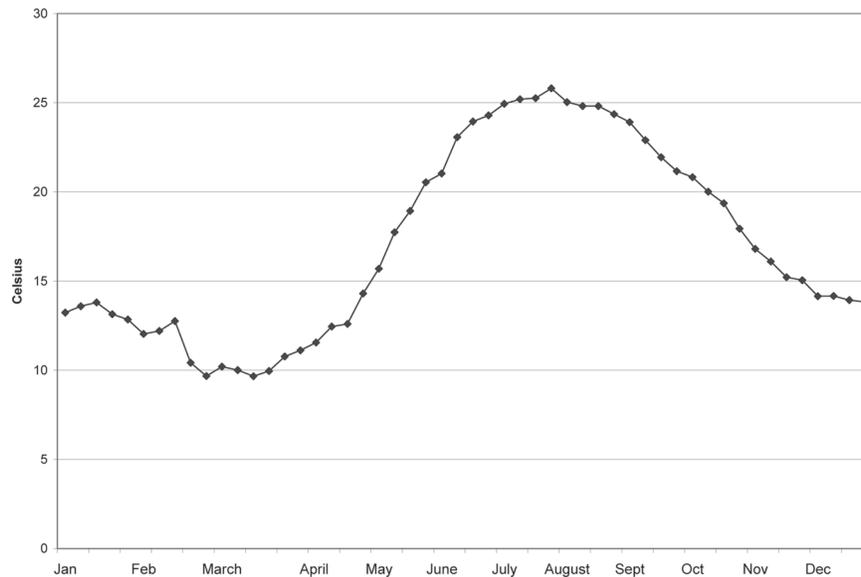
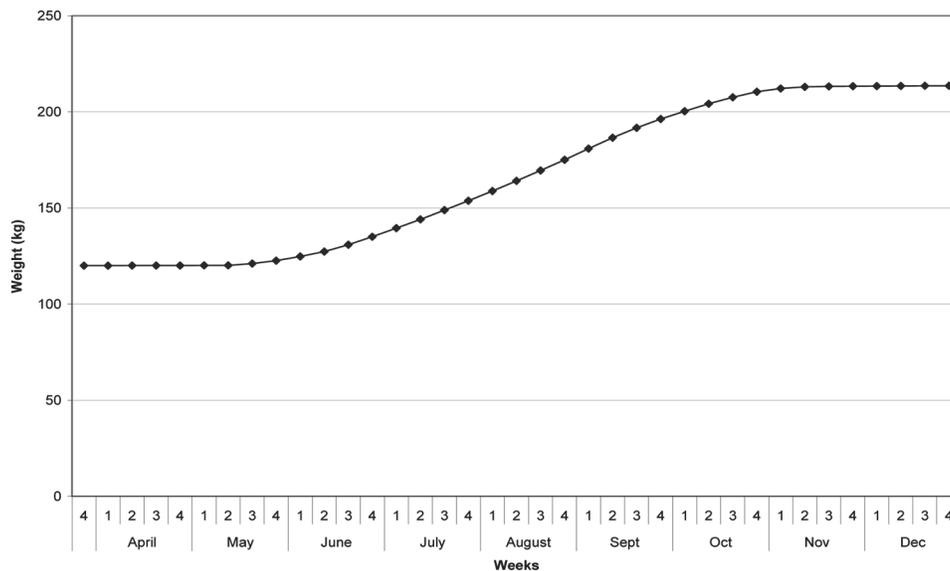


FIGURE 1 Hypothetical water temperature regime.

by the prevailing water temperature regime for a given farming location. It is assumed that the farming of bluefin tuna would not take place at temperatures colder than 10 degrees Celsius, since the bluefin tuna would not be able to tolerate such temperatures for an extended period of time confined in the cages; therefore, the number of weeks in the year that can accommodate farming activity is truncated according to this biological constraint. Given an assumed starting weight of 120 kilograms<sup>2</sup> for wild-caught bluefin tuna, the change in the expected weight of a bluefin tuna located in the assumed water temperature regime is depicted in Figure 2.

Water temperatures will be specified as stochastic in the model, allowing for a divergence between the expected change in weight over a farming season and the actual change in weight of a bluefin tuna over a farming season. The farmer uses the average weekly water temperature based on five years of observations as the expectation for weekly water temperatures. Actual water temperatures will be drawn from a triangle distribution defined by the average of 5 years of weekly observations and upper and lower bounds corresponding to the maximum and minimum observed water temperatures over the 5-year period. Any divergence between the expected and actual water temperatures will imply a deviation between the expected growth of the fish and the actual growth of the fish over the course of a week. Actual changes in the weight of the fish over the course of a week will be incorporated iteratively in the model to capture

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**FIGURE 2** Increase in weight for a 120 kg bluefin tuna based on hypothetical water temperature regime.

situations where the fish may grow faster or slower than the expected rate of growth.

### Mortality

As is the case with modeling the growth of farmed bluefin tuna, modeling the mortality rate of farmed bluefin tuna is not an easy task given substantial data limitations. It is worth noting that the term mortality rate used here refers strictly to the natural mortality rate as opposed to referring to mortality associated with fishing pressure. In theory, the mortality rate could be a function of the following parameters: age of the fish, the weight of the fish, water temperature, density of the fish in the pen, feed quantity and feed quality. In the literature, mortality rates for bluefin tuna farming operations are commonly reported as rates over the course of the entire farming season, ranging from 2–50% or more depending on the country and location (Katavic et al., 2002, 2003a; Hayward et al., 2007; Ticina et al., 2007).

The mortality rates presented in the literature are not presented as a function of any variables; therefore, given this lack of information, the mortality rate specified in this model is not a function of any key variables. Rather, to reflect the uncertainty facing a new farmer who would have little information regarding the weekly expected mortality rate for the operation, the mortality rate is specified as a stochastic parameter. This parameter is defined and drawn from a triangle distribution based on observed mortality rates in other countries. For this exposition, a triangle distribution for the weekly mortality rate defined by (0/0.0125/0.0225) is used to solve the bioeconomic model.

### ECONOMIC SUB-MODEL

#### Price Component

The price function used within the model is adapted from Carroll et al. (2001), who estimated a hedonic price function for Atlantic bluefin tuna. The modified version of the price function used is:

$$\ln P_t = \varphi + \sum_i \beta_i G_{i,t} + \beta_5 \ln W_t + \beta_6 W_t + \beta_7 \ln H_t \quad (4)$$

where

$P(t)$  = Price per kilogram (dressed weight) of an individual bluefin tuna.

$\varphi$  = Aggregation of constant parameters.

$G_i(t)$  = Grade of an individual fish at time  $t$ ,

where  $i$  = Color, Freshness, Fat Content, and Shape.

$W(t)$  = Weight (kg) of an individual fish at time  $t$ .

$H(t)$  = Harvest (number) of US Bluefin tuna at time  $t$ .

Price is a function of weight and harvest quantity of fish at time  $t$  from the United States on the Tsukiji market. It is implicitly assumed that a farmer controls all of the fish being sent to the Tsukiji market from the United States. This assumption of farm size is reasonable given that a single tuna farming operation in Mexico produced 1,500 MT of farmed tuna in 2005. This quantity of production by a single operation is nearly equivalent to the entire quota available to the U.S. East Coast for the 2008 fishing year (1,668.9 MT). All variables of the hedonic price function are set at their mean values, except for the endogenous variables Dressed Weight, U.S. Harvest Quantity and the four grade variables. At present there is no estimated relationship capturing the effect of how a given increase in weight translates into a given increase in fat content. In lieu of this lack of empirical data, the model assumes that the grades of the fish, including the fat content grade of the fish, entering the farming operation evolve over time in proportion to the increase in body weight over the relevant time period. Since increases in the weight of a fish over the course of a farming season implicitly involve an increase in the fat content of the fish, this assumption allows for the incorporation of both weight and fat content changes over time despite a lack of empirical data linking the two explicitly.

### Initial Capital Expenditures

This section itemizes the initial capital expenditures for an offshore bluefin tuna farming enterprise. It is assumed that an operation would need the following equipment for the offshore production of farmed bluefin tuna: towing cages, grow-out cages, a harvesting and feeding vessel, a dive vessel, dive equipment, anchors, weights, and other mooring equipment (Table 1). These items are assumed to be purchased at their current market prices. The information and prices presented in Table 1 are based upon personal communication with a leading expert and supplier of bluefin tuna farming equipment (G. Johnson, personal communication, June 28, 2008). Permit costs associated with the establishment of the farm that are incurred prior to production are also included in the initial capital expenditures.

The number of cages required by the operation is determined by calculating the number of pens needed to accommodate a stocking density of  $4\text{ kg/m}^3$  given the starting biomass of fish. This stocking density was chosen because it was once the industry-wide regulation in the Australian

TABLE 1 Initial Capital Investments

Initial Investment for an Offshore Bluefin Tuna Farming Operation						
Item	Number	Unit price	Initial investment	Years of use ful life	Salvage value	Annual depreciation
Cages and Mooring Equipment						
Towing Cage (50 × 25 m) supplied, constructed on-site and launched	1	\$82,000	\$82,000	5	0	\$16,400
Towing ropes, bridles, weights, etc. (per set)	1	\$26,000	\$26,000	5	0	\$5,200
Towing Net	1	\$41,000	\$41,000	5	0	\$8,200
Towing Cage		Subtotal	\$149,000			
Mooring System per cage based on a grid system	2	\$20,000	\$40,000	5	0	\$8,000
Farm cage triple ring collar (holding/on-growing)	2	\$117,000	\$234,000	5	0	\$46,800
Farm site holding net	2	\$35,000	\$70,000	5	0	\$14,000
Sea Freight per complete unit	2	\$23,000	\$46,000	5	0	\$9,200
Grow-out Cage		Subtotal	\$390,000			
Vessels						
Diving vessels	2	\$103,321	\$206,642	10	\$10,000	\$19,664
Diving and sundry equipment	1	\$75,000	\$75,000	5	0	\$15,000
Spares based on six cages	1	\$51,000	\$51,000	5	0	\$10,200
Aquaculture Support Vessel	1	\$250,000	\$250,000	10	\$10,000	\$24,000
Vessels		Subtotal	\$582,642			
Permits and Licenses						
Permit Costs	1	\$10,000	\$10,000			
Total Initial Investment			\$1,131,642			
Total Annual Depreciation						\$176,664

Southern bluefin tuna farming industry and it represents a reasonable value given the range of stocking densities found in the literature (Primary Industries & Resources South Australia, 2000; Colak et al., 2003; Katavic et al., 2003c; Ticina et al., 2007). The cages are assumed to be 50 m in diameter and 25 m in depth, which is a prevalent size for the industry, although cage dimensions can vary by country (Lioka et al., 2000; Katavic et al., 2003a; Ottolenghi et al., 2004; Aguado-Gimenez & Garcia-Garcia, 2005a; Zertuche-Gonzalez et al., 2008).

### Fixed Cost Components

The towing and grow-out cages, harvesting and feeding vessel, diving vessels, diving equipment, anchors, weights, and other mooring equipment are purchased at their market prices as specified in Table 1. Given assumptions for the years of useful life and salvage values, the assets

are depreciated according to the straight-line method (Table 1). The interest on the principal of the loan stemming from the initial capital expenditures itemized in Table 1 is calculated according to a standard amortization of a fixed rate 5-year loan with a 7% annual interest rate. A 5-year loan was chosen since the majority of the equipment has a useful life of 5 years and would require replacement in the middle of a 10-year operating horizon. Each year, the operation is assumed to incur annual costs (\$50,000) associated with docking and insuring the vessels. The operation also incurs annual repair and maintenance costs associated with maintaining the cages, equipment and vessels. These costs are assumed to be \$60,000. This value is taken from a study that assessed the economics of the offshore aquaculture production of Pacific threadfin in Hawaii (Kam et al., 2003).

### Variable Cost Components

*Acquisition Costs.* The acquisition of wild-caught bluefin tuna is an important stage of production and source of cost for an operator. The acquisition of bluefin tuna can be modeled in a variety of ways to capture the complexity of the process. In this paper, acquisition costs will be specified as a deterministic process where the starting number and starting weight of the fish are known with certainty *ex ante*. This is a reasonable assumption given the fisheries management regime for Atlantic bluefin tuna, where the quota allocated to the fishery is known prior to the start of the season (ICCAT, 2008). Operators would know ahead of time exactly how many fish could be legally obtained for that season. Due to the high value and demand for bluefin tuna, it is reasonable to assume that operators would catch 100% of the quota allocated to that sector in a given season. Therefore, the initial starting number of bluefin tuna ( $N_0$ ) is treated as an exogenous variable rather than a decision variable within the model.

Based on data gathered during a site visit to a bluefin tuna farming facility in Cartagena, Spain, the acquisition costs in the Spanish bluefin tuna farming industry are estimated to be \$6,000 USD/day and the boats are hired for a minimum of 45 days (ANATUN, 2007). Assuming the number of days required for acquiring all of the wild bluefin tuna available under the quota is 45 days, the total acquisition costs associated with towing the fish are estimated to be \$270,000. The tuna farms also have to pay the purse seiners who are contracted to catch the fish. The prevailing rate in the Spanish tuna farming industry in 2007 was \$9 USD/kg for live-caught purse seined bluefin tuna (ANATUN, 2007). Therefore, the model calculates both the cost associated with catching wild bluefin tuna (reflected in the price paid to the purse seiners for harvesting wild-caught

live bluefin) as well as the cost associated with towing the bluefin tuna back to the farm site (since the purse seiners are not well-suited to tow cages back to the farm site). The variable  $A_0$  in Equation (1) is an aggregation of both sources of cost.

*Labor Costs.* There are three tiers of workers in the bioeconomic model (manager, diver, and general labor). The number of workers, type of worker and hours worked during the season can be flexibly specified within the model. The default number of workers required to operate a farm is four divers, four general laborers and one manager. This ratio is held constant within the model and the total number of workers is scaled up in this fixed proportion according to the total number of pens that comprise the farm. In this way the labor requirements associated with different farm configurations can be captured in the model. The wage rate for each tier of worker can be specified in the model, as well as the number of hours worked per week and per season. Thus, some labor can be specified as seasonal while other labor can be classified as year-round.

Since it is assumed that the number of fish available to the farming operation is known with certainty prior to the start of the farming season, a farming operation will know how many pens it will require prior to the start of the season. Given these assumptions, the farm size and resulting labor requirements are known with certainty *ex ante*. Table 2 itemizes the three classifications of labor and their respective hourly rates. The hourly rates are in line with those cited in the literature for other aquaculture operations, as well as those cited by a job web site for aquaculture technicians (Kam et al., 2003; Think Trades and Technology, 2008).

*Feed Costs.* Using the estimates of weekly quantity of feed consumed per fish, one can solve for the weekly feed costs per fish.

$$WFC_t = QFW_t * FC \quad (5)$$

where

$WFC_t$  = Weekly average feed costs per individual fish

$FC$  = Feed costs (\$/kg)

This methodology does not explicitly model the effect of differences in feed quality on the observed growth rate of a farmed bluefin tuna. It is assumed that the quantity of feed consumed will be a ration that provides the nutritional content necessary to result in the observed increase in biomass. In reality, the quality of the feed consumed will influence the accumulation of weight and fat, as well as the overall health, quality and condition of the fish.

TABLE 2 Key Model Parameters

Parameter	Value	Units	Description
$W_0$	120	Kilograms (kg)	Starting weight of wild bluefin tuna at $t_0$
Available Quota	800	Metric Tons (MT)	Quota of Atlantic bluefin tuna available for farming purposes
$N_0$	6,666	Number of fish	Starting number of wild bluefin tuna at $t_0$
Stocking Density	4	Kg/m <sup>3</sup>	Stocking Density in Pens
FeedCost	0.50	USD/kg	Feed Costs
FCR	20	Number	Feed Conversion Ratio
Acquisition Costs	9	USD/kg	Cost per kg of wild bluefin tuna caught by purse seiners
Towing Costs	6,000	USD/day	Cost per day paid to tug boats to tow wild caught bluefin tuna back to the farm site
Towing Days	45	Days	Number of days required to tow the fish to the farm site
Vessel Payload	100	Metric Tons (MT)	Payload of Vessel
Vessel Speed	10	Knots/Hour	Vessel speed per hour
Dist.	10	Nautical Miles	Distance of Pens from Shore
Fuel Cost	3	USD/gallon	Vessel diesel fuel costs per gallon
$C_{HC}$	1	USD/fish	Per fish harvesting cost
Managerial Labor	\$40.00	USD/hour	Managerial Hourly Rate
Skilled Diver Labor	\$30.00	USD/hour	Skilled Diver Hourly Rate
General Labor	\$20.00	USD/hour	General Labor Hourly Rate
$T$	37	Weeks	Length of the Farming Season
$r$	0.14%	Percent/week	Weekly Discount Rate
$i$	7%	Percent/year	Annual Interest Rate of loan used to finance initial capital expenditures.

*Vessel Costs.* Another relevant variable cost for the offshore operation is weekly vessel transportation costs associated with feeding the fish and/or harvesting the fish. The model estimates the weekly number of roundtrip needed for either harvesting or feeding and chooses the maximum of those values.

$$WT_t = \max \left( \frac{QFW_t}{\text{Payload}}, \frac{H_t}{\text{Payload}} \right) \tag{6}$$

where

- $WT_t$  = Number of weekly vessel trips
- $QFW_t$  = Quantity of feed fed to an individual fish per week
- $H_t$  = Quantity of fish harvested per week
- Payload = Payload of Vessel (measured in kilograms)

Once the number of weekly trips is known, this value is multiplied by the cost of a vessel trip, in order to determine the total weekly vessel trip

costs. Vessel trip costs are defined by the following:

$$VC = \left( \frac{\text{Dist} \cdot VGH}{\text{Speed} \cdot 60} \right)^2 * \text{Fuel Costs} \quad (7)$$

where

$$\begin{aligned} VC &= \text{Weekly vessel trip costs} \\ \text{Dist} &= \text{Nautical miles from shore} \\ \text{Speed} &= \text{Vessel Steaming Speed (knots)} \\ \text{Fuel Costs} &= \text{\$/gallon} \\ VGH &= \text{Vessel Gallons per hour.} \end{aligned}$$

*Harvesting Costs.* Harvest costs are specified to be a constant cost per unit. This value is multiplied by the quantity of fish harvested each week to solve for total weekly harvesting costs. The default value in this model is 1 USD/fish harvested; however, this value can be easily changed within the model to discern the effect of different harvesting costs on the optimal harvest schedule and overall economic feasibility of the operation.

## MODEL IMPLEMENTATION

The bioeconomic model has been developed and coded to be highly adaptable. All key parameters and equations in the model can be customized by the user to reflect different locations, scenarios, and starting values. This makes the model capable of analyzing offshore bluefin tuna farming anywhere in the world. Ultimately this model will be used to analyze the economic feasibility of farmed bluefin tuna production in the United States; however, for now the model as parameterized is very general in order to demonstrate the model's performance and key features.

In the analysis that follows, the model has been parameterized with data acquired from an actual site visit to a farming facility in Cartagena, Spain, data obtained from consultation with experts in the field, and data from available peer-reviewed and gray literature. In future applications of this model, these variables will take on site-specific values; however, for now the values for key variables including the available quota, starting weight, and water temperature regime have been posited to demonstrate the performance of the model. The values of key model starting parameters are specified in Table 2. It is assumed that there is always a market for bluefin tuna at the estimated prices. Net returns are calculated before taxes are taken into account.

## RESULTS

The power of the dynamic stochastic adaptive bioeconomic model is that under situations where parameters are not known with certainty, the adaptive nature of the model allows the farmer to adjust to deviations from parameter estimates that were specified *ex ante*. This ability to adjust to stochasticity in-season allows the farmer to identify a harvest schedule that is either equal to or superior to an optimal harvest schedule identified through a non-adaptive model. Further, it is more realistic to model the behavior of a farmer in this manner because farmers are constantly observing and adjusting production decisions in response to changes in key parameters.

In the model presented here, two parameters are defined as stochastic: the weekly mortality rate and the weekly water temperature for the assumed location. Both variables will be defined by triangle distributions to capture the underlying stochasticity associated with those key parameters. In the case of the mortality rate, the farmer will form an expectation of the expected weekly mortality rate in order to solve for the optimal harvest schedule. At the end of the period, the farmer observes the actual mortality rate and incorporates this new information into the bioeconomic model by updating the expectation for next period's mortality rate. This new expectation is then used to solve for the profit maximizing harvest schedule for the remaining periods. The manner in which the farmer updates expectations can be formulated to be as simple or as complex as the user desires. In this specification of the model, the farmer updates expectations through a simple averaging of observations over the course of a farming season.

Stochastic water temperatures are incorporated into the model as follows. The farmer's expectation of weekly water temperatures over the course of a farming season will be the mean observed water temperature based on the average of 5 years of actual water temperature data. This information will be used to define the farmer's expectation of growth over a farming season, which ultimately influences the optimal harvest decision of the farmer. However, actual weekly water temperatures will be drawn from a triangle distribution and these values will determine the actual growth of the fish over the course of a week, which may or may not deviate from the expected growth of the fish for that period. Thus, the model will update the actual growth of the fish week to week to reflect actual growth as opposed to expected growth over a period. In future applications of this model, additional parameters can be specified as stochastic, including economic variables such as price and feed costs.

The bioeconomic model was run 100 times to simulate 100 different bioeconomically optimized farming seasons and their associated revenues,

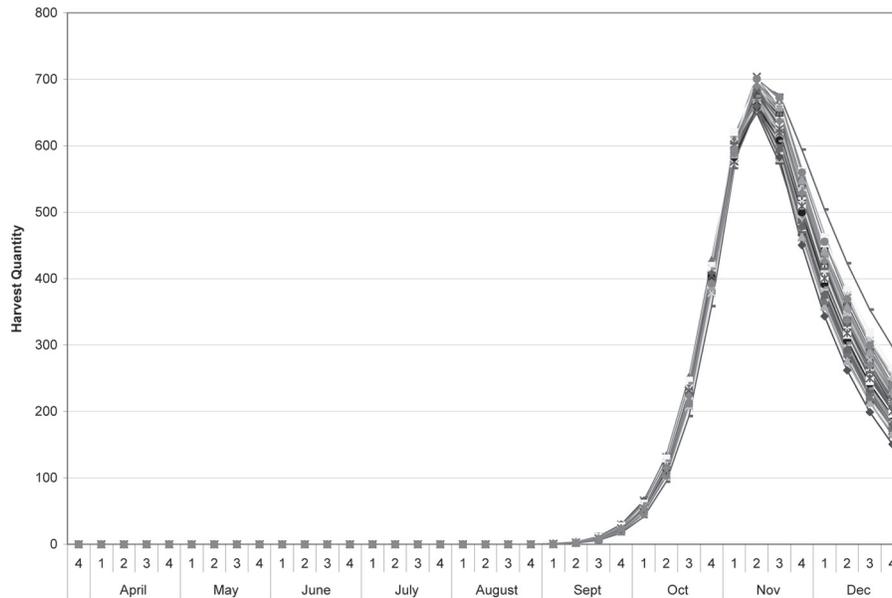


FIGURE 3 Optimal harvest schedules based on 100 runs.

costs, and optimal harvest schedules. Figure 3 presents the optimal harvest schedules associated with 100 runs of the model. Since the bioeconomic model is a finite horizon model, each farming season is independent. Thus, each of the 100 runs can be viewed as a possible yearly outcome for a farmer. From these 100 possible yearly iterations, the bioeconomic model then randomly chooses 10 iterations from this larger set of 100 iterations to construct one possible representation of a 10-year operating horizon in order to solve for the expected NPV and expected IRR. This process of selecting 10 random yearly iterations to calculate the expected NPV and IRR values to simulate the performance of a 10-year operation is repeated 100 times. Figures 4 and 5 present histograms of the expected NPV and expected IRR for an enterprise operating over a 10-year horizon under the assumed parameter values.

## CONCLUSIONS

This research establishes a bioeconomic framework for modeling the economics of farmed bluefin tuna production through the use of a dynamic stochastic adaptive bioeconomic model. Under stochastic conditions, the adaptive model is able to provide results that are superior to non-adaptive models that do not allow an operator to adapt in-season. The application of this bioeconomic model to offshore bluefin tuna farming allows for the quantification of the economic benefits and costs

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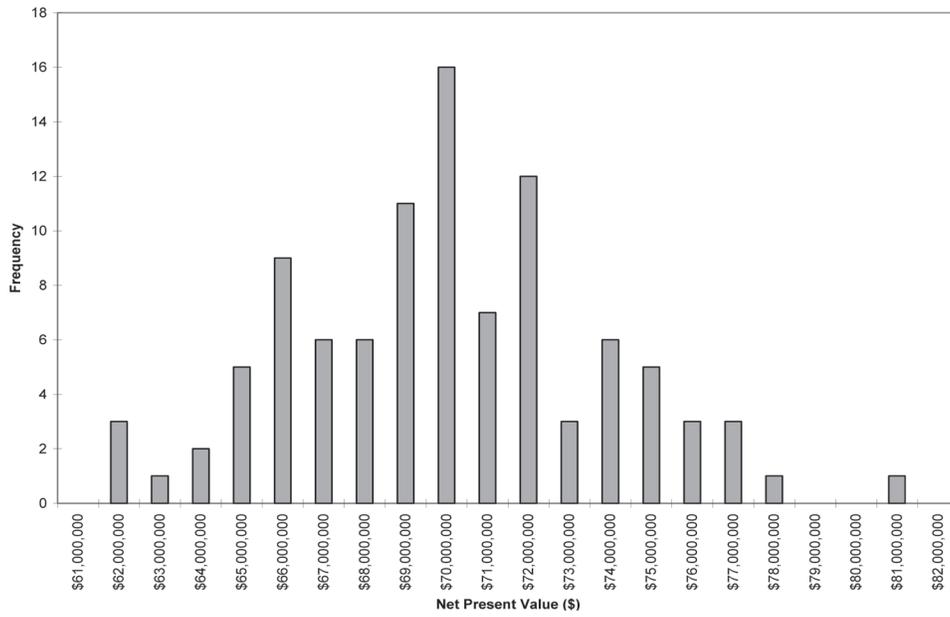


FIGURE 4 Expected net present value of a ten-year farming operation.

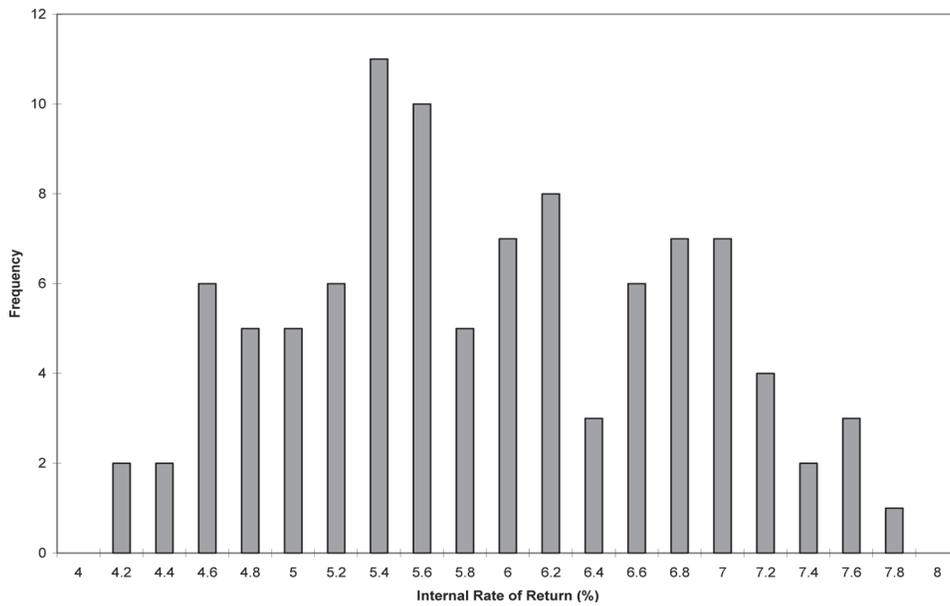


FIGURE 5 Expected internal rate of return for a ten-year farming operation.

associated with the farming of bluefin tuna, in particular the impact on the optimal harvest decision in situations where key variables are uncertain or are known to be stochastic. As better data becomes available, the model can be refined to reflect more sophisticated formulations and relationships among key variables. Regardless, this model is a first step in quantifying and empirically modeling the economics of this form of production. The next step of this research is to apply site-specific production parameters to the bioeconomic model to assess the economic feasibility of this form of production on the U.S. East Coast under a variety of economic, biological and regulatory conditions.

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### NOTES

1. The site chosen for this exposition corresponds to Virginia Beach, VA (Station ID 44014).
2. This value was chosen since it represents an industry observed size-at-capture for wild-caught bluefin tuna in the Spanish bluefin tuna farming industry.

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