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Economic Evaluation of Capture-Based Bluefin Tuna Aquaculture on the US East Coast

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Abstract *This article assesses the economic feasibility of capture-based bluefin tuna aquaculture on the US East Coast and examines the potential of this hybrid form of aquaculture production to increase the net economic value generated in the US East Coast bluefin tuna fishery. A bioeconomic model of an offshore capture-based bluefin tuna aquaculture facility is used to evaluate the economic feasibility of this form of production on the US East Coast under a variety of economic, biological, and regulatory assumptions. The results suggest that of the three proposed farming sites along the US East Coast, the expected net present value (NPV) of the operation over a 10-year operating horizon is highest at the Gray's Reef, GA, site. The second part of this article assesses the extent to which the opportunity to engage in capture-based bluefin tuna aquaculture production could improve the net economic value generated in the US East Coast bluefin tuna fishery. The results suggest that if the fishery had the opportunity to engage in capture-based bluefin tuna aquaculture production, there would be an increase in the net revenue generated in the fishery. Depending on how the seasonal quota was enforced, economic improvement in the fishery ranged from a 52–142% improvement in net revenue. Even when the cost per fish associated with capture-based bluefin tuna aquaculture production was doubled, the results still indicated that the opportunity to engage in capture-based bluefin tuna aquaculture production would lead to a 12% increase in net revenue in the fishery.*

Key words Capture-based aquaculture, bioeconomic modeling, bluefin tuna, fisheries management.

JEL Classification Codes Q22, Q27, Q28, C61.

Introduction

This article seeks to answer two important and interrelated questions. The first question is to evaluate whether the practice of capture-based bluefin tuna aquaculture production on the US East Coast could be economically feasible. The second is to evaluate the extent to which capture-based bluefin tuna aquaculture production could increase the net economic value generated in the US East Coast bluefin tuna fishery. In order to answer the first question, a bioeconomic modeling framework developed by Shamshak and Anderson (2009) is parameterized with data specific to the US East Coast. Economic feasibility is evaluated under a variety of biological, economic, and regulatory assumptions. In order to answer the second question, the economic value of the US East Coast bluefin tuna fishery is estimated with and without the opportunity to engage in capture-based bluefin tuna aquaculture production. Net revenues in the US East Coast bluefin tuna fishery were previously estimated by Martinez-Garmendia and Anderson (2005). Their research incorporated important influences on the price and weight of fish caught in the US Western

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Atlantic bluefin tuna fishery by explicitly incorporating the effect of harvesting practices on the attribute (quality) grades of an individual fish caught by a particular gear, area, and week in the US bluefin tuna fishery. A capture-based bluefin tuna aquaculture sector is incorporated into this existing modeling framework in order to evaluate the potential economic improvement associated with the opportunity to engage in this form of production in the US East Coast bluefin tuna fishery.

Background

Historically, the US East Coast has been a major supplier of high quality, wild-caught bluefin tuna to Japan. While there has been interest in capture-based bluefin tuna aquaculture production on the US East Coast among some industry participants, to date there are no commercial operations. Capture-based aquaculture refers to production that is based on the capture of wild species (as opposed to hatchery-reared species) for stocking and growout purposes. Examples of capture-based aquaculture production include eels, groupers, yellowtails, and tunas (Ottolenghi *et al.* 2004). Capture-based bluefin tuna aquaculture has also been referred to as bluefin tuna ranching, farming, or fattening. The only bluefin tuna farming conducted on the US East Coast was a research project involving the New England Aquarium that investigated the feeding of juvenile bluefin tuna 25 miles off the coast of Virginia in 1996. Currently, the only capture-based bluefin tuna aquaculture operations in North America are in Mexican waters off the coast of Baja California, Mexico.

Assessing the economics of capture-based bluefin tuna aquaculture, and in particular the economic feasibility of this form of production on the US East Coast, is useful given the continued expansion of bluefin tuna farming globally and uncertainty regarding the economic feasibility of capture-based bluefin tuna aquaculture production in the US. Capture-based bluefin tuna aquaculture production has expanded rapidly, transforming how bluefin tuna is supplied to the market. Currently, all three species of bluefin tuna (Atlantic, Pacific, and Southern) are farmed in Japan, Australia, Mexico, and in Mediterranean countries, including, but not limited to Croatia, Spain, Malta, and Turkey. In 1991, the farming of Southern bluefin tuna (SBT) was established in Port Lincoln, Australia. At that time, 3% of the Australian total allowable catch (TAC) for SBT was directed into the farming sector. Currently, more than 98% of the Australian SBT quota is directed into the farming sector (DAFF 2007). In Australia, this form of capture-based production has led to an increase in the economic value of the SBT fishery. The economic incentive to fatten bluefin tuna relates to the manner in which bluefin tuna is priced in the market. All things being equal, a fish with a higher fat content will receive a higher price in the market (Carroll, Anderson, and Martinez-Garmendia 2001). Another benefit of capture-based production, as compared to traditional fisheries-based production, is that it allows the producer the ability to time the market and focus on gaining the highest economic value for each fish harvested. Thus, capture-based aquaculture production has the potential to increase the economic value of a fishery without increasing the amount of biomass extracted from it. It is important to note that sustainable fisheries management should be about more than just getting the numbers right; *i.e.*, harvesting the correct number of fish to ensure biological sustainability. Rather, fishery managers should also be concerned with whether the resource, once harvested, is being put towards its most valuable use. Capture-based bluefin tuna aquaculture production is one means by which the extracted resource's value can be maximized. Therefore, if fishery managers can optimally manage and enforce the quota from a biological standpoint, then capture-based production could be a sustainable form of production that maximizes the economic value of the fishery. More generally, there is no doubt that aquaculture can be carried out in a sustainable manner, independent of the level of intensity. Rather, the real issue regarding aquaculture and sustainability is whether farmers choose to use sustainable practices (Asche 2008).

This notion of sustainable aquaculture, and more specifically of sustainable bluefin tuna aquaculture, is not exclusive to economists. Barbara Block, a Stanford University marine biologist and leading bluefin tuna researcher recently commented that "there are people out there and I am one of them, who believe there could be a future with sustainable aquaculture for tuna" (Eilperin 2009). Author Richard Ellis echoed a similar theme, stating that "The only way to save the bluefin…may be to domesticate the species" (Ellis 2008). The capture-based bluefin tuna industry recognizes that reliance on wild bluefin tuna stocks limits the growth of the industry. However, the success of capture-based aquaculture production has provided the economic incentive and financial ability to engage in research and development to close the life cycle for bluefin tuna. Australian and European researchers have successfully created artificial breeding regimes for Southern bluefin tuna and Atlantic bluefin tuna, respectively (Clean Seas Tuna Limited 2008a,b). This is a major step towards the closed-cycle breeding of bluefin tuna for farming purposes, and possibly for stock enhancement purposes. Furthermore, as the knowledge base for bluefin tuna expands, the industry will better understand the nutritional needs of bluefin tuna, possibly leading to the development of a pelleted feed. The transition to a pelleted feed is another key hurdle for the industry, as it seeks to reduce its reliance of wild-caught forage fish. Thus, the emergence and success of capture-based bluefin tuna production has provided the economic incentives to engage in research and development programs that could ultimately benefit wild bluefin tuna and forage fish populations. Some experts anticipate that bluefin tuna fingerlings will be commercially available within the next two years (Vitalini *et al.* 2010).

Specification of the Model for the US East Coast

Shamshak and Anderson (2009) developed a bioeconomic framework for assessing the economic feasibility of an offshore capture-based bluefin tuna aquaculture operation by specifying a dynamic stochastic adaptive bioeconomic model of an offshore capture-based production facility. This bioeconomic modeling framework is used to examine the economic feasibility of bluefin tuna farming on the US East Coast. Given that there are currently no active commercial bluefin tuna farming operations on the US East Coast, this article evaluates the economics of bluefin tuna farming based upon data acquired from a site visit to a capture-based Atlantic bluefin tuna farming facility in Cartagena, Spain, consultation with experts in the field, and from available peer-reviewed and gray literature (Shamshak 2009).

The objective function for a risk-neutral, profit-maximizing offshore bluefin tuna aquaculture producer as specified by Shamshak and Anderson (2009) is:

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

subject to:

$$P_t = P_t(W_t, H_t, G_{it})$$

$$W_t = f(FCR_t, FR_t\ (WT_t))$$

$$G_{i,t} = G_{t-1} + \left(\frac{W_t - W_{t-1}}{W_T - W_{(0)}}\right) \cdot (G_T - G_{(0)})$$

$$N_t = N_{t-1}(1 - M_{t-1}) - H_{t-1}$$

$$N_t, H_t \geq 0$$

$$N(0) = N_0,$$

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_{VCt} = *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 model identifies the weekly 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. For a more detailed description of the bioeconomic model and its sub-components, see Shamshak and Anderson (2009) or Shamshak (2009). Identifying the optimal harvest schedule for a producer is critical, since one of the most important managerial activities in production planning is determining the optimal rotation (Guttormsen 2008).

Modeling Site-specific Growth

Growth over the course of a week is modeled in a manner that captures the influences of water temperature (WT_t), feeding rate, and feed conversion ratio (*FCR*) on the increase in weight of an individual fish (W_t). A relationship between water temperature and daily feeding rate was estimated from the research of Katavic, Ticina, and Francicevic (2003a) on farmed Atlantic bluefin tuna in Croatia (Shamshak and Anderson 2009). 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, Ticina, and Franicevic 2003b; Ottolenghi *et al.* 2004; Aguado-Gimenez and Garcia-Garcia 2005). In order to solve equation 2, a water temperature regime must be specified:

$$W_{t+1} = W_t + \frac{(1.29WT_t - 20.29)W_t \cdot 6}{FCR}. \tag{2}$$

Three sites along the US East Coast have been identified as potential locations for bluefin tuna farming facilities: Nantucket, MA; Virginia Beach, VA; and Gray's Reef, GA. These sites were chosen to capture a range of potential production environments along the US East Coast.[1] All three farming sites are assumed to be located 10 nautical miles offshore. The Virginia Beach, VA, site is a particularly reasonable location to assess, since in 1996 the New England Aquarium conducted a juvenile bluefin tuna feeding experiment 25 miles off the coast of Virginia Beach, VA. Estimates of the average weekly water temperatures at each of the three sites were gathered from the NOAA National Data Buoy Center database (National Oceanic and Atmospheric Administration (NOAA) 2010). Figure 1 presents the average weekly water temperature for each area based on the average of five years of data observations. Based on the reported water temperatures associated with bluefin farming operations in other countries, the water temperature regimes reflected by these three US sites capture a reasonable range of production environments.[2]

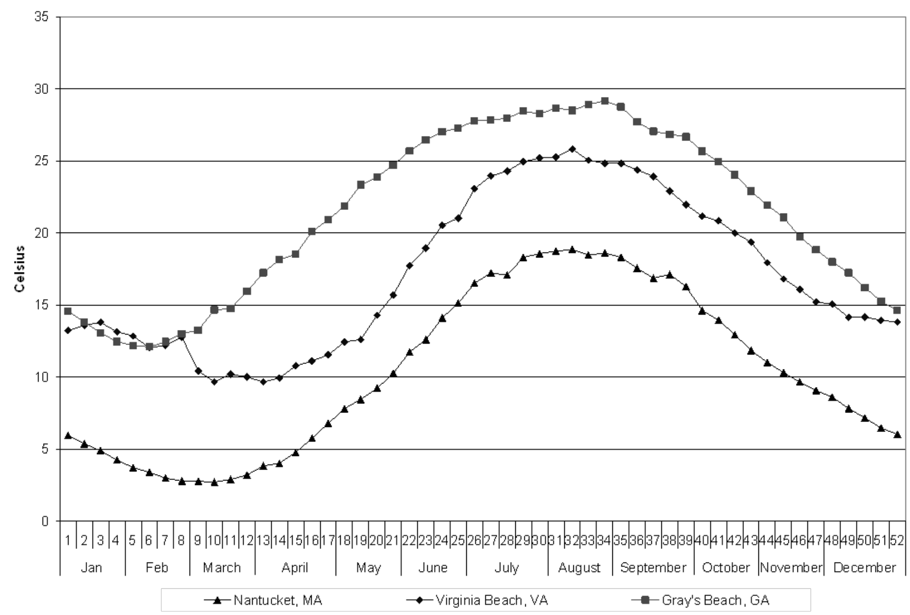

Figure 1. Average Weekly Water Temperature (Celsius) by Location

[1] The sites were chosen to demonstrate a range of temperature-dependent growth profiles along the US East Coast. The sites were not chosen with specific consideration for conflicts with other marine users, including marine mammals, nor were they chosen based upon consideration of hurricanes, dead zones, red tide events, or other important factors that could influence the ultimate location of an offshore facility. Another important consideration is the degree to which the various stakeholders in the US East Coast fishery would be receptive to capture-based aquaculture development. Chu *et al.* (2010) discusses important factors influencing stakeholders' perceptions of aquaculture, both in the US and Norway.

[2] Farmed bluefin tuna production typically takes place in water temperature ranging from 12–26°C (54–79°F) (Caill-Milly *et al.* 2003; Ticina, Katavic, and Grubisic 2007).

Specifying Site-specific Seasonal Scenarios

Season length for each location is influenced by three factors: regulatory constraints stipulating the start and end of the fishing season, the prevailing water temperature regime for a given location, and the availability of bluefin tuna in the vicinity of the farming location.[3] It is assumed that the farming of bluefin tuna would not take place in water temperatures colder than 10°C, since they would not be able to tolerate such temperatures for an extended period of time confined in the net pens (Magnusson *et al.* 1994; Block *et al.* 2001). Therefore, the number of weeks in the year that can accommodate farming activity for a particular location is truncated according to this biological constraint.

The following assumptions regarding the migratory behavior of the bluefin tuna over the course of a calendar year dictates whether the fish would be physically available for capture near a given location, provided the fishing season was open. The migratory assumptions are based on tagging data, which suggest that bluefin tuna are typically located off the coast of North Carolina over the winter months from approximately December to mid-March (Block *et al.* 2005). The fish then migrate down the US East Coast and enter the Gulf of Mexico to spawn. The fish will remain in the Gulf of Mexico from April to the end of May. From June onward, the fish exit the Gulf of Mexico and proceed up the US East Coast. By late June/early July the fish are in the vicinity of Nantucket, MA. Once the waters begin to cool, the bluefin tuna then migrate either back down towards the mid-Atlantic or across the Atlantic to the Mediterranean Sea. This migration back down the coast typically begins in early October, and by the beginning of December, the fish are again located off the coast of North Carolina.

Further, it is assumed that the starting weight of a wild-caught bluefin tuna will vary by site owing to the natural fluctuations in its weight over the course of a year. It is assumed that a 120 kg fish exits the waters near North Carolina around early March and enters and remains in the Gulf of Mexico to spawn during the months of April and May. It has been estimated that bluefin tuna lose 14.73% of their weight between their pre- and post-spawn states; therefore, the model assumes that bluefin tuna exiting the Gulf of Mexico in June will have lost that percentage of their weight due to spawning (Rodriguez-Roda 1964). Once the fish exits the Gulf of Mexico, it will first pass the Gray's Reef, GA, site. The fish is at an assumed weight of 102 kg at this time of year for this location (table 1). Based on estimates of the growth of a wild bluefin tuna during the summer months, it is assumed that a wild bluefin tuna migrating up the coast will increase its body weigh 7% each month. Therefore, a fish at the Virginia Beach, VA, location is assumed to weigh 106 kg, while a fish at the Nantucket, MA, location is assumed to weigh 109 kg. By October, the fish is assumed to weigh 132 kg, owing to the assumed increase in weight of a wild bluefin tuna over the summer months.

Given this expected migration route, the following possible farming seasons emerge. Following the exit of the bluefin tuna from the Gulf of Mexico, the farming season in Gray's Reef, GA, commences the first week of June and runs until December 31. For the Virginia Beach, VA, location, the bluefin tuna pass the Virginia Beach, VA, site twice during the calendar year. Therefore, two different farming seasons will be explored for this location. The first possible season would commence the second week of June and continue until December 31. Alternatively, the farming season could commence in early October after the fish have migrated down from the New England waters and continue until December 31. Finally, the farming season for the Nantucket, MA, location will begin the first week of July and continue until the second week of November, when the

[3] Historically the NMFS Atlantic Tuna Program operated from June 1–December 31. However starting in 2008, the fishing season was extended from January 1–December 31. Despite this change, some categories (general category, harpoon, and purse seine) still have limitations on the commencement and duration of the fishing seasons (NMFS 2010).

expected weekly water temperature falls below 10°C. The resulting available weeks for farming by location based on the constraints and assumptions specified above are: Nantucket, MA (20 weeks); Virginia Beach, VA (29 weeks if the fish are caught in June; 13 weeks if the fish are caught in October); and Gray's Reef, GA (31 weeks).

Table 1
Assumptions Regarding Seasonal Migration and Weight of Wild Bluefin Tuna

Time of Year	Location	Stocking Weight (W_0)
January–March	North Carolina	120 kg
Mid-March–April	Migrate to the Gulf of Mexico	120 kg
April–June	Spawning in the Gulf of Mexico	120 kg
June	Gray's Reef, GA	102 kg
Mid-June	Virginia Beach, VA	106 kg
Late June	Nantucket, MA	109 kg
October	Migrate South to VA	132 kg
December	Migrate South to North Carolina	140 kg

The starting number and stocking weight of bluefin tuna are assumed to be known with certainty at the beginning of the farming season. Acquisition costs are also assumed to be known with certainty and are set as a fixed cost per day. Acquisition costs are not assumed to vary by site; rather it is assumed that if the bluefin tuna are within the vicinity of the farming site, then the costs of acquiring those fish are identical across locations. 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. The estimates of acquisition and towing costs used within the model were obtained by a site visit to a capture-based farming facility in Cartagena, Spain (table 2). These values are consistent with another study reporting acquisition costs for the more general Mediterranean fishery (Ottolenghi 2008).

The maximum number of wild-caught bluefin tuna available for farming in a year is assumed to be exogenously determined. For the 2009 fishing year, the baseline allocation of quota allocated to the Western Atlantic (US East Coast) bluefin tuna fishery was 1,009.9 MT. This quota was allocated across seven categories: General (475.7 MT), Harpoon (39.4 MT), Angling (199.0 MT), Longline (81.8 MT), Purse Seine (187.8MT), Trap (1.0 MT), and Reserve (25.2MT). The total quota for the 2009 fishing year includes the baseline allocation of quota for the US Atlantic bluefin tuna fishery plus 517.5 MT of under-harvested quota from the 2008 fishing year. The presence of a quota for Western Atlantic bluefin tuna limits the total amount of wild-caught bluefin tuna available for farming purposes and may impact the economic feasibility of offshore tuna farming on the US East Coast. It is assumed that the baseline allocation of bluefin tuna (and not the adjusted allocation of quota including under-harvested quota) would be available for capture by a farming sector. Further, it is assumed that a single farming operation would operate on the US East Coast, controlling the entire allocation of bluefin tuna (1,000 MT). This assumed size for a single operation is reasonable given the existence of farming operations in Mexico and Spain, which produce 1,500 MT of farmed bluefin tuna (Anonymous 2005).

Table 2
Key Model Parameters

Parameter	Value	Unit	Description
Stocking weight (W_0)	See table 1	Kilograms (kg)	Stocking weight of wild bluefin tuna at t_0
Available quota	1,000	Metric tons (MT)	Quota of Atlantic bluefin tuna avail able for farming purposes
Stocking density	4	Kg/m^3	Stocking density in pens
Feed cost	$0.1	USD/kg	Feed costs per kilogram
FCR	20	Number	Feed conversion ratio
Acquisition costs	$9.00	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 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
FuelCost	$3.00	USD/gallon	Vessel diesel fuel costs per gallon
C_{HC}	$1.00	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
r	5%	Percent	Discount rate
i	7%	Percent	Annual interest rate of loan used to finance initial capital expenditures
m	10%	Percent	Annual interest rate for operational loan

Price Function

The price function used in the model is adapted from Carroll, Anderson, and Martinez-Garmendia (2001) and takes the form:

$$\ln P_t = \varphi + \sum_i \beta_i G_{i,t} + \beta_5 \ln W_t + \beta_6 W_t + \beta_7 \ln H_t, \tag{3}$$

where:

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

Incorporating Stochasticity into the Model

A number of key parameters in the model are specified as stochastic in order to capture the inherent uncertainty associated with those values. In order to capture uncertainty surrounding seasonal growth in the model, weekly water temperatures are specified as stochastic in the model, allowing for a divergence between the expected change in weekly weight over a farming season and the actual change in weekly weight of a bluefin tuna over a farming season.[4]

In order to incorporate stochasticity associated with the price received in the Tsukiji market, a triangle distribution is defined for each of the coefficients estimated by Carroll, Anderson, and Martinez-Garmendia (2001) (table 3). This method for incorporating stochasticity into the price function allows the model to capture deviations between the expected market price and the actual market price. The rationale for making price stochastic within the model is that a producer would most likely not be able to perfectly predict the weekly market price. Furthermore, incorporating uncertainty around the price received is important given that prices in this model influence both the optimal harvest decision as well as the magnitude of the expected NPV of the operation over a 10-year operating horizon.

Table 3
Coefficients and P Values in Parentheses for the Bluefin Tuna Hedonic Price Equation

Parameter	Description	Coefficient
α	Intercept	0.3660 (0.5049)
FR	Freshness	0.0409 (0.0808)
FT	Fat content	0.3326 (0.0000)
CL	Color	0.2486 (0.0000)
SH	Shape	0.1927 (0.0000)
DRW	Dressed weight	0.5901 (0.0000)
Exp(DRW)	Exponential dressed weight	–0.0021 (0.0000)
CONS	Consignment	0.0588 (0.0013)
XPORT	Export	0.5176 (0.0000)
AVGXRATE	Average yen/$US rate	–0.9050 (0.0000)
US	Number of US bluefin tuna in Tsukiji (per week)	–0.0518 (0.0000)
JAP	Number of Japanese bluefin tuna in Tsukiji (per week)	–0.0516 (0.0000)
AVGJap	Mean number of Japanese bluefin tuna in Tsukiji (per week)	59.57*

* This mean value is based on 11,715 observations, with a minimum value of 0.00 and a maximum value of 726.00 (Carroll, Anderson, and Martinez-Garmendia 2001).

Note: Taken from Carroll, Anderson, and Martinez-Garmendia (2001).

[4] A triangle distribution defined by the average of five years of weekly observations and upper and lower bounds corresponding to the maximum and minimum observed water temperatures over a five-year period is used in the model (Shamshak 2009).

An empirical relationship describing the mortality rate associated with the farming of bluefin tuna is difficult to ascertain. The mortality rates found in literature are commonly reported for the entire farming season rather than as a function of time or other key variables. In lieu of this data, seasonal mortality rates from the literature are used to specify a triangle distribution for the weekly mortality rate within the model. In this manner, the mortality rate can be defined to vary each week, capturing the inherent uncertainty in the magnitude and variability of this parameter over the course of a farming season. Additionally, this method captures the uncertainty facing a new operator who would have little knowledge regarding the expected weekly mortality rate for the operation.

The model incorporates three sources of mortality: mortality associated with towing the fish to the farm site, on-farm mortality over the course of a farming season, and low probability/high mortality events like storms or other conflicts with marine users.

The model assumes a uniform distribution (0, 0.05) for the expected towing mortality rate. This mortality rate was chosen since it corresponds to observed data in the industry pertaining to the mortality rate for this stage of production (Shamshak 2009). It is further assumed that these fish are not sold; however, the lost fish are still a cost to the farming operation, since the cost of acquiring those lost or dead tuna is still incurred.

The mortality rate used in the stochastic specification of the on-farm weekly mortality rate in this model will be randomly generated from a triangle distribution based on the observed mortality rates in other countries (Shamshak 2009).[5] The triangle distribution defined in the baseline formulation of the model is (0/0.65/1.25), where the lower bound of the expected mortality rate is zero, the average expected mortality rate is 0.65% per week, and the upper bound of the expected mortality rate is 1.25% per week. For all three locations, this triangle distribution of the weekly mortality rate results in a seasonal mortality rate (the mortality rate calculated for the entire farming season) in the range of 12–30%. This range for the expected seasonal mortality rate is comparable to observed mortality rates in the industry (Katavic, Ticina, and Franicevic 2002, 2003a; Hayward, Aiken, and Nowak 2007; Martinez 2007; Zertuche-Gonzalez *et al.* 2008).

In addition to the mortality associated with the feeding and fattening of bluefin tuna, there are other sources of mortality that could occur with a low probability. However, if these events do occur, they could result in a large loss of fish. Such events include the potential for a shark or other marine mammal to enter the tuna cages and consume the fish or stress them to the point they perish. This type of event has occurred in Australia and Mexico (Hassan 2003). Another possibility would be a storm event that damages the cages. In 2007, an entire farm (1,500 MT of bluefin tuna) was lost during a storm in Malta (Shamshak 2009). There could be a loss of fish due to a collision between the farm site and a boat or other marine user. In Mexico a fishing vessel struck and became encircled by a 90-meter tuna pen, resulting in the loss of some fish (Culora 2008).

Therefore, in order to model these low probability/potentially high mortality events, it will be assumed that 99.99% of the time, the weekly mortality rate is drawn from the triangle distribution (0/0.65/1.25). This leaves a 0.01% per week probability that a low probability/high mortality event will occur. If a low probability/high mortality does occur, the mortality rate will be drawn from a uniform distribution (0.4, 1.0), reflecting an equal probability of an event causing anywhere from 40–100% mortality on the farm.

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[5] When the underlying distribution of a variable is unknown, a useful specification is the triangle distribution. There are three key parameters that comprise this distribution: the mean, a lower bound, and an upper bound. Expert opinion can be used to establish minimum, maximum, and expected values. In this way, the stochastic nature of the variable can be captured and modeled despite a lack of knowledge regarding the true underlying distribution of a variable.

Fixed and Variable Costs

The fixed and variable costs used in the model are presented in table 2. A more detailed description of these variables is available in Shamshak and Anderson (2009).

Other Assumptions

It is assumed that there is always a market for farmed bluefin tuna at the estimated prices. Net returns are calculated before taxes are taken into account. The model calculates the overall NPV of the operation over a 10-year operating horizon with a discount rate of 5%. Other relevant model parameters and their baseline values are listed in table 2. It is worth noting that prices and costs are not assumed to appreciate or depreciate over the course of a 10-year operating horizon.

Results

The model is run 100 times, each time using a different set of randomly drawn stochastic variables (table 4). Thus, each of the 100 runs can be viewed as 100 different possible yearly outcomes. From these 100 possible yearly iterations, the bioeconomic model then randomly chooses 10 iterations from this larger set of 100 to construct one possible representation of a 10-year operating horizon in order to solve for the expected NPV of the farming operation. This process of selecting 10 random yearly iterations is repeated 100 times in order to calculate the expected NPV for a 10-year operating horizon (table 5).

The model keeps track of the cash flow of the operation over a 10-year operating horizon. When the cash flow is not sufficient to cover the wild-caught bluefin tuna acquisition costs, the model initiates an operational loan to be paid in full at the end of the farming season. Tracking the cash flow ensures that the financial performance of the operation remains above some threshold of equity over the course of a 10-year operating horizon. The rule of thumb for determining if an operation is insolvent is if the operation has a negative net worth that exceeds the wild-caught bluefin tuna acquisition costs. If this threshold condition is met, the operation is deemed insolvent, and the NPV for that 10-year operation is zero. While it may be that the firm could have positive net earnings in future years of the model and return to a positive cash flow over the course of the 10-year operating horizon, it is assumed that no lending institution would be willing to bear that risk by extending a loan to a firm that has a net worth below some set threshold amount.

The results demonstrate that the farming site with the highest expected NPV is Gray's Reef, GA (table 4 & 5). This result makes sense, since this farming location has the warmest seasonal water temperatures, and thus, daily feeding rates and growth are higher at this site, *ceteris paribus*. Also, the length of the season is the longest at this site, which also implies a longer time to increase the weight and fat content of the fish. However, the probability of failure is also highest at this site, owing to the fact that the farming season is the longest and thus, the operation has a greater chance of a high mortality event occurring. The Gray's Reef, GA, site also has the highest expected gross and break-even price per fish harvested. In contrast, the site with the lowest expected NPV, gross revenue, and break-even price per fish is Nantucket, MA. At this site, water temperatures are the coolest relative to the other two sites.

The results also examine the tradeoff facing a farmer at the Virginia Beach, VA, site who has a choice between initiating a farming season in June or initiating a farming season in October. On one hand, the farmer can take advantage of the natural growth and appreciation in the quality (and hence economic value) of the fish that will occur in the wild. Although the fish increases its weight in the wild for 'free,' that appreciation in

Table 4
Single Season Expected Net Revenue by Location (Based on 100 Runs)

Area	Massachusetts		Virginia		Virginia		Georgia	
Season length	June–Nov. (20 weeks)		June–Dec. (29 weeks)		Oct.–Dec. (13 weeks)		June–Dec. (31 weeks)	
Stocking weight	109		106		132		102	
	Expected Value	% of Total Cost	Expected Value	% of Total Cost	Expected Value	% of Total Cost	Expected Value	% of Total Cost
Gross revenue	$20,880,540		$34,333,810		$21,802,311		$44,584,970	
Feed costs	$239,014	2.2	$1,351,044	11.7	$226,079	2.2	$2,110,561	17.1
Vessel trip costs	$8,959	0.1	$19,157	0.2	$5,882	0.1	$24,449	0.2
Harvesting costs	$7,859	0.1	$7,698	0.1	$6,810	0.1	$7,648	0.1
Labor costs	$560,000	5.4	$560,000	4.8	$560,000	5.4	$560,000	4.5
Acquisition costs	$9,458,009	91.2	$9,538,865	82.3	$9,394,356	91.2	$9,557,098	77.3
Maintenance costs	$60,000	0.6	$60,000	0.5	$60,000	0.6	$60,000	0.5
Lease costs	$50,000	0.5	$50,000	0.4	$50,000	0.5	$50,000	0.4
NPV	$10,496,697		$22,747,055		$11,499,184		$32,215,215	
IRR	0.4%		2.9%		1.8%		3.50%	
Mortality rate	12%		16%		8%		20%	
Prob. of failure	2%		3%		3%		4%	
Gross revenue /fish	$2,657		$4,460		$3,201		$5,830	
Break-even revenue/fish	$1,321		$1,505		$1,513		$1,617	
Average price/kg	$22.10		$23.87		$22.98		$24.39	

weight does not rival the appreciation in weight that can occur under a farming scenario. Wild bluefin tuna typically increase their body weight by 7% per month during the summer months. However, while the fish is feeding voraciously, they are also constantly engaged in activities that burn energy—energy that could be used to put on weight but instead is lost in swimming, avoiding predators, and hunting for fish. Thus, within a farming environment more weight can be put on during the same amount of time because the fish are consistently fed, and because they do not have to hunt for food or avoid predators. For example, in June, a fish weighing 106 kg will put on 23 kg in the wild until the first week of October, which is a 21% increase in weight through 'natural feeding.' In contrast, a 106 kg fish in a farming operation will put on 58 kg by the first week of October, which is a 53% increase in weight through controlled feeding. Thus, the growth and increase in value associated with farming bluefin tuna exceeds that of leaving fish in the wild to appreciate in weight naturally before capture. Therefore, initiating a farming season in October at the Virginia Beach, VA, site does not make economic sense for the farmer.

Table 5

Ten-Year Expected Economic Performance by Location (Based on 100 Runs)

Area	Massachusetts	Virginia	Virginia	Georgia
Season Length	June–Nov. (20 weeks)	June–Dec. (29 weeks)	Oct.–Dec. (13 weeks)	June–Dec. (31 weeks)
Stocking Weight	109	106	132	102
Expected NPV	$81,725,169	$169,300,969	$88,209,366	$244,471,702
Minimum	$50,961,966	($9,633,853)	$57,781,954	($10,929,100)
Maximum	$105,014,479	$212,430,612	$116,054,727	$331,511,066

Evaluating the Potential to Increase the Economic Value of the US East Coast Bluefin Tuna Fishery

The remainder of this article evaluates the extent to which the opportunity to engage in capture-based bluefin tuna aquaculture production could increase the net economic value generated in the fishery. Martinez-Garmendia and Anderson (2005) estimated net revenues in the US East Coast bluefin tuna fishery by explicitly incorporating the effect of harvesting practices on the attribute (quality) grades of an individual fish caught by a particular gear, area, and week in the US bluefin tuna fishery. The attribute grades, in turn, directly influence the prices received by fishermen. Using a hedonic price function estimated by Carroll, Anderson, and Martinez-Garmendia (2001), one can directly link choices regarding harvest location, gear type, and time of week in the fishing season to the price and weight of a particular fish caught under those circumstances. The objective function formulated by Martinez-Garmendia and Anderson (2005) is as follows:

$$\underset{x_{w,a,g}}{Max} \quad \prod = \sum_{w=24}^{42} \sum_{a=1,2,3,4,5\&6,7,8} \sum_{g=RR,HARP1,HARP2,PS,LL} x_{w,a,g} \left[DRW(x_{w,a,g}) P_{w,a,g} - c_g \right]. \quad (4)$$

RR and HARP1 refer to the rod and reel and harpoon categories defined by the general category; HARP2 is the harpoon category; PS is the purse seine category; and LL is the long line category; DRW is the dressed weight in pounds, and P is the price per pound. The price function ($P_{w,a,g}$) used in Martinez-Garmendia and Anderson (2005) is identical to equation 3 in this article. The coefficients associated with the price function are presented in table 3. The attribute grades (A_i) used within the price function (freshness (*FR*), fat content (*FT*), color (*CL*), shape (*SH*), and dressed weight (*DRW*)) are functions of harvest practices:

$$A_i = \eta_i + \sum_{g=RR,HARP1,HARP2,PS,LL} \delta_{ig} D_g + \sum_{a=1,2,3,4,5\&6,7,8} \phi_{ia} D_a + \sum_{w=24}^{42} \varphi_{iw} D_w. \quad (5)$$

$$\forall i = FR, FT, CL, SH, DRW$$

Solving equation 4 involves determining the optimal number of fish caught in a particular week, by area, and by gear combination ($x_{w,a,g}$), such that the solution maximizes the net revenues in the fishery. The total amount of fish harvested is limited by a yearly quota (*Q*) set by the National Marine Fisheries Service (NMFS). The quota used by Martinez-Garmendia and Anderson (2005) was 1,075 metric tons (mt). For consistency with prior results, this article assumes a quota of 1,075 mt:[6]

$$\sum_{w=24}^{42} \sum_{a=1,2,3,4,5\&6,7,8} \sum_{g=RR,HARP1,HARP2,PS,LL} x_{w,a,g} \leq Q. \quad (6)$$

The cost of a fish caught by a particular gear type is assumed to be $1,960 for the general category, $1,147 for the harpoon category, and $1,730 for both the purse seine and long line categories (National Marine Fisheries Service (NMFS) 1998; Martinez-Garmendia, and Anderson 2005).

For analysis of capture-based bluefin tuna aquaculture, it is assumed that a farming operation would take place under the Gray's Reef, GA, scenario due to the fact that this scenario had the highest NPV, as determined in the first part of this research. The initial stocking weight of farmed bluefin tuna is 102 kg, and this value is taken from the bio-economic model presented in the first half of the article.[7] The per-fish cost of a farmed bluefin tuna is assumed to be equal to the break-even price of farmed bluefin tuna as calculated for the Gray's Beach, GA, farming operation (table 4).

The results of Martinez-Garmendia and Anderson (2005) cannot be precisely replicated due to the fact that Martinez-Garmendia and Anderson used actual weekly harvest quantities from Japan to calculate the hedonic price function in their model. Without access to this weekly data set, the only available data on weekly harvest quantities from Japan is the mean value reported (AVGJAP) in Carroll, Anderson, and Martinez-Garmendia 2001 (table 3). Thus, the magnitude of the net revenue in the fishery as estimated by Martinez-Garmendia and Anderson (2005) cannot be identically reproduced. However, reproducing the model using the point estimate for weekly harvest quantities from Japan (AVGJAP) as an estimate of the weekly harvest of bluefin tuna from Japan results in identical harvest weeks and gear types as found in Martinez-Garmendia and Anderson (2005) (table 6).

[6] For comparison, the adjusted quota of bluefin tuna for the 2010 fishing season was 1,168.2 mt. The adjusted quota includes carrying forward 388.6 mt of under-harvest from the 2009 quota.
[7] This whole weight is converted to dressed weight using a conversion factor of 1.25, as defined by the International Commission for the Conservation of Atlantic Tunas (ICCAT) (Miyake *et al.* 2003).

Table 6
Bluefin Tuna Harvest (Number of Fish) Per Week: Comparing the Results of Martinez-Garmendia and Anderson (2005) and the Re-estimated Model

Week	Area	Results of Martinez-Garmendia and Anderson (2005) TOTAL	Re-estimated Model TOTAL
24	3	14	14
25	3	0	0
26	3	1	16
27	3	1	11
28	3	1	10
29	3	2	11
30	3	3	11
31	3	11	12
32	3	177	18
33	3	87	32
34	3	22	50
35	7	165	190
36	3	95	102
37	3	73	394
38	7	944	996
39	7	2,175	1,298
40	3	610	554
41	7	1,224	1,480
42	3	867	548
Total Harvest		6,470	5,747
Net Revenue		$13,870,250	$9,460,600

Economic Performance without Capture-based Production

Martinez-Garmendia and Anderson (2005) found that net revenues in the US East Coast bluefin tuna fishery could be increased if the seasonal quota limits for each gear type were eliminated. The rationale for this result is that requiring a certain quantity of fish to be caught by certain gears at specific times of the year ignores important market considerations, primarily the economic gain associated with delaying harvest until later in the season and also the economic gain associated with harvesting fish with gears that correspond to higher attribute grades. Martinez-Garmendia and Anderson (2005) found that profits in the fishery could be maximized by allowing the fishery to consolidate harvests into areas 3 and 7, using harpoons, across the available weeks in the season (table 6). More importantly, instead of requiring harvest quantities to be spread out across the season, their analysis found that net revenues could be increased if the fishery was allowed to shift the allocation of harvested fish closer to the end of the season (Martinez-Garmendia and Anderson 2005). Typically, supply spikes lead to a reduction in the price per pound received; however, the results suggest that the negative impact of an increasing number of fish harvested towards the end of the season is offset by the seasonal improvement in the quality of the fish (Martinez-Garmendia and Anderson 2005). Re-estimating the model using the point estimate for weekly harvest quantities from Japan (AVGJAP) results in a net revenue of $9,460,600 for the US East Coast fishery (table 6).

Economic Performance with Capture-based Production

In order to incorporate the opportunity to engage in capture-based bluefin tuna aquaculture production into this modeling framework, bluefin tuna farming is treated as an additional gear type of choice in the fishery. The objective of bluefin tuna farming is to increase both the weight and fat content of the fish over the course of a season. As a result, the incorporation of capture-based production in this framework leads to a situation where the quantity of fish harvested in the season is further consolidated into the latter weeks of the season. This result can be seen by comparing the results presented in table 7 versus the results presented in table 6. The economic rationale for this outcome is that towards the end of the season the fish have increased in weight and have appreciated in attribute grades (primarily fat content). As such, the economic return associated with harvesting a fish is greatest under a farming operation at the end of the season (table 7). The harvest quantity spikes at the end of the season; however, the economic return associated with the appreciation in weight and quality of the fish offsets the negative impact on price.

Table 7 presents three columns of results, all of which involve the integration of capture-based production into equation 4. The first column is associated with counting the final harvest weight against the seasonal quota (Q). This imposition of quota at the end of the season provides a lower bound on the possible increase in net revenue of the fishery given the option to farm bluefin tuna. Since the final harvest weight of the fish is counted against the quota, the gain in weight from farming, and not just the starting biomass removed from the fishery, is included in the calculation. This scenario results in net revenue of $14,471,000 in the fishery, a 52% improvement over the case where there is no bluefin tuna farming option in the fishery ($9,460,600).

If the total biomass that is placed into the pens at the beginning of the farming season is instead counted against the quota, then the net revenue associated with that scenario increases relative to the end-of-season case (column 2 vs. column 1 of table 7). The net revenue under this scenario is $22,987,722, a 142% improvement over the case where there is no bluefin tuna farming option in the fishery ($9,460,600). It is worth noting that when the total biomass entering the pens at the start of the season is counted against the quota, this implies a certain starting number of fish. In order to be realistic, the model incorporates a 20% mortality rate for the farmed fish over the course of the farming season. Furthermore, it is assumed that these fish are not sold, thereby providing an even more conservative estimate of the potential net revenue in the fishery.

Finally, the last column of table 7 examines the net revenue generated assuming the per-fish cost associated with farming bluefin tuna is doubled from the baseline value of $1,617 to $3,234. While the weekly harvest quantities are still concentrated towards the end of the season, there is an increase in the number of weeks in which fish are harvested relative to the other two scenarios presented in table 7. In effect, increasing the cost of a farmed fish serves to shift the optimal harvest profile closer to the present. The impact of doubling the cost of a farmed fish impacts the net revenues generated in the fishery ($10,630,532); however, this scenario still results in a 12% improvement over the case where there is no opportunity to engage in capture-based bluefin tuna aquaculture in the fishery (table 7).

These results are a logical extension of the results of Martinez-Garmendia and Anderson (2005). They found that the accumulation of harvest towards the end of the season improved the economic performance of the fishery. Similarly, comparing the net economic value of the fishery without capture-based bluefin tuna aquaculture as estimated in this article ($9,490,600) to the net economic value of the fishery with capture-based aquaculture production results in an increase in the net revenue generated in the US East Coast bluefin tuna fishery.

Table 7
Per-week Harvest of Bluefin Tuna

	Quota Based on Final Harvest Weight		Quota Based on Starting Stocking Weight		Quota Based on Starting Stocking Weight with 100% Increase in Cost Per Fish ($3,234 vs. baseline value of $1,617)		
Week	Area	Capture-based Aquaculture	Area	Capture-based Aquaculture	Area	Capture-based Aquaculture	Traditional Fishery
24							
25							
26							
27							
28							
29							
30							
31							
32							
33							
34							
35					7		2
36					7		2
37					7		4
38					7		10
39	6	2			7		14
40	6	6	6	1	7		6
41	6	14	6	5	7		16
42	6	4,606	6	7,641	6	7,541	
Totals		4,628		7,647		7,541	54
Net revenue		$14,471,000		$22,987,722		$10,630,532	
Improvement with Capture-based Aquaculture		52%		142%		12%	

Conclusion

The first objective of this research was to evaluate the economic feasibility of capture-based bluefin tuna aquaculture on the US East Coast under a variety of biological, economic, and regulatory assumptions. The results of the bioeconomic optimization suggest that a farming facility located 10 nautical miles off the coast of Gray's Reef, GA, would generate the greatest NPV over the course of a 10-year operating horizon. Next, the economic performance of the entire US East Coast bluefin tuna fishery was evaluated using the results obtained in the first part of this research. Evaluating the economic performance of the fishery with and without the opportunity to engage in capture-based bluefin tuna aquaculture production revealed that with the opportunity to farm bluefin tuna, the net revenue generated in the fishery could be increased. Depending on how the seasonal quota was enforced, economic improvement in the fishery ranged from a 52–142% improvement in net revenue. Even when the cost per fish associated with bluefin tuna farming was doubled, the results still indicated that the opportunity to engage in capture-based production would lead to a 12% increase in net revenue in the fishery. The results of this article support the findings of Martinez-Garmendia and Anderson (2005), which suggested that net revenues in the US East Coast fishery could be increased if the fishery was allowed to shift the allocation of harvested fish towards the end of the season. Furthermore, the results of this research demonstrate that net revenues in the fishery could be further improved if the fishery had the option to engage in capture-based bluefin tuna aquaculture production.

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