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SIMULATION BASED OPTIMIZATION IN FISHERY MANAGEMENT

Farhad Azadivar

College of Engineering
University of Massachusetts, Dartmouth
North Dartmouth, MA 02747, U.S.A.

Tu Truong

Department of Industrial and
Manufacturing Systems Engineering
Kansas State University
Manhattan, KS 66506, U.S.A.

Kevin D.E. Stokesbury
Brian J. Rothschild

School for Marine Science and Technology
University of Massachusetts, Dartmouth
New Bedford, MA 02744, U.S.A.

ABSTRACT

The sea scallop resource of Georges Bank supports one of the largest commercial fisheries in the United States. The objective of this research was to develop a technique to examine different management strategies for the sea scallop resource of Georges Bank and compare these strategies to the optimal. A simulation model followed the sea scallop population dynamics using information from recent photographic surveys and studies on spatial and temporal life history parameters, such as growth, natural mortality, spawning, and fishing activities. Stochastic simulation technique was used to describe the influence of the highly variable marine environment. Genetic Algorithm technique was used to develop harvest strategy in the area for optimal utilization by maximizing long term fishing yield. Simulation and Genetic Algorithm are combined to solve the optimization problem. Simulation returns performance measures for a given policy and Genetic Algorithm provides the search process to obtain the optimum policy.

1 INTRODUCTION

Georges Bank covers an area of 315 km $\times$ 222 km (69,930 km^2) in the Northwest Atlantic Ocean. It is one of the largest scallop aggregation in the world and a primary groundfish resource. Presently sea scallops are the second most valuable fishery in New England. High exploitation rates of groundfish in the early nineties significantly reduced the total fishing yields and endangered the sustainability of the Georges Bank ecosystem. To rebuilt the ground-fish resource, three large areas were closed to all mobile fishing gear including sea scallop dredges, in Dec 1994 (Figure 1). These closed areas included large portions of the sea scallop fishing grounds.

The complexity of this fisheries management stems from the dynamic nature of the marine environment and numerous interest groups with different objectives. One of the first objectives is to maximize long-term benefit from marine resources. To accomplish this a set of control mechanisms have been developed. These are:

(a) *Fishing capacity restrictions.* Fishing permits limit the number of fishing vessels, the number of crew a vessel can carry and the number of days at sea (DAS) a vessel can fish.
(b) *Gear restrictions.* The type, amount and ring-size of scallop dredge.
(c) *Area specific restrictions*. Controlling where fishing can take place at any given time in the year.

Since 1999, the School for Marine Science and Technology, University of Massachusetts, Dartmouth (SMAST) has conducted photographic surveys of the scallop fishing grounds of Georges Bank. Tagging experiments and laboratory experiments indicate different growth and recruitment rates and "meat-weight-to-shell-height" relationship for scallops in different locations. These spatial variations must be incorporated into the fisheries management model.

The SMAST photographic surveys provide high-resolution scallop density and shell height frequencies. The scallop grounds were sampled on a 1.57 km grid (0.85 nautical miles). At each station a survey vessel deployed the

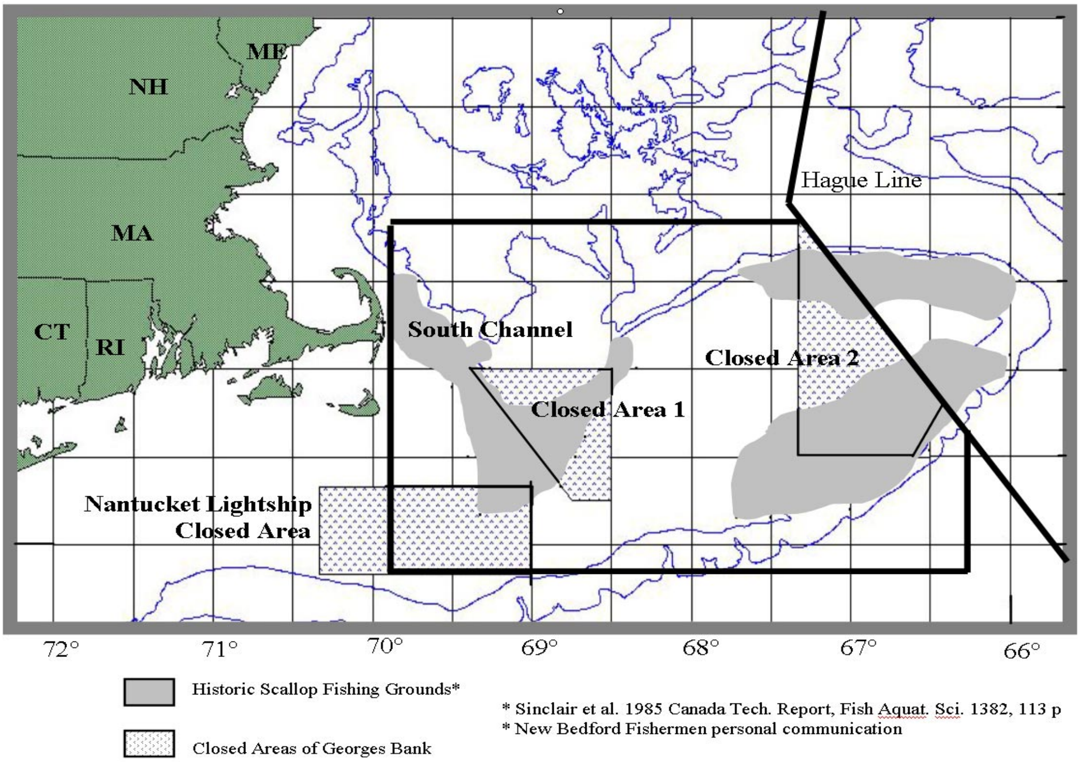

Figure 1: Closed Areas and Historic Sea Scallop Fishing Grounds of Georges Bank

video camera mounted on the sampling pyramid providing a 2.8 m^2 image of the sea floor. Four quadrats within a 100-200 meter radius were filmed at each station and the scallops within each quadrat were counted and measured (Stokesbury 2002).

Kriging was used to estimate scallop densities in non-sampled areas. Kriging is a generalized linear regression technique used to calculate the spatial variation of an organisms mean density. Kriging has been successfully applied in many fields of geo-statistics (Stein 1999, Stokesbury et al. 2001).

2 SCALLOP BIOLOGY AND SCALLOP FISHERY

Sea scallop growth was described using the von Bertalanffy equation (Haddon 2001):

$$L_t = L_\infty.[1-e^{-K(t-t_0)}] \quad (1)$$

where L_t is scallop shell height at year t; L_∞ is the theoretical maximum scallop shell height; K is the Brody growth coefficient; and t_0 is the hypothetical age where the scallop has a shell height of zero. In this work, $L_\infty = 170$ (mm), K=0.3 and t_0=0.

The instantaneous natural mortality rate of sea scallops is estimated as M = 0.1 is equivalent to 9% annual loss (Caddy 1989).

Sea scallop recruitment was described using the Ricker model (Haddon 2001):

$$R = \alpha.SS.e^{-\beta.SS}.e^{N(\mu,\sigma)} \quad (2)$$

where R is the number of recruits in one year per area unit; SS is density of adult scallops (or spawning stock); $N(\mu, \sigma)$ represents a normally distributed random number with mean μ, standard deviation σ. Parameters α, β, μ and σ for each sub region are estimated based on survey data from 1979 to 2000 (SAFE 2000).

Ninety percent of landed scallops are harvested with dredges. Typical scallop vessels are equipped with two 4.6 m wide dredges with 8.9 cm rings. The gear selectivity equation is:

$$p(h) = \begin{cases} 0 & h \leq H\text{-}10 \\ (h\text{-}H+10)/20 & H\text{-}10 < h \leq H+10 \\ 1 & h > H+10 \end{cases} \quad (3)$$

where h is scallop shell height in mm; H is the net's ring diameter in mm; and p(h) is the probability of a scallop with shell height h being retained in a net.

3 MODELING AND SIMULATION

A simulation model estimated scallop abundance over years and annual fishing yields. The Georges Bank's scallop abundance was modeled over a fine grid of 170×120. Each cell represents one square nautical mile (3.42 km^2). The simulation model used one-year increments. Scallops were grouped into *N* categories based on shell height.

Let S denote the number of sub-areas that are created for management, T denote the number of years in the planning horizon, $V_{st} = [n_{s1t}\ n_{s2t} \ldots n_{sNt}]$ denote population vector of sub-area *s* at the beginning of year *t*, and n_{srt} denote the number of scallops in the r-th category in sub-area *s* in year *t*.

As scallops grow, they shift from the r_1-th category to the r_2-th category. The population vector is updated at the end of the year before natural mortality and fishing mortality are applied

$$V_{st'} = [G_s].V_{st} \tag{4}$$

where $[G_s]$ is $N \times N$ matrix represents the growing process of scallops in sub-area s during one time interval.

$$g_{r_1,r_2} = \begin{cases} 1 & \text{if scallop in the } r_1 \text{ - th category will be in the } r_2 \text{ - th category after one year} \\ 0 & \text{otherwise} \end{cases}$$

Natural mortality and fishing mortality are continuous processes that occur in parallel causing the number of scallops to decline exponentially. While natural mortality (M = 0.1) is assumed to be the same in all categories, fishing mortality varies.

Let *M* be instantaneous natural mortality and F_{srt} be instantaneous fishing mortality for the r-th category in sub-area s in year t.

$$n_{sr(t+1)} = n_{srt}.e^{-(M+F_{srt})} \,. \tag{5}$$

If F_{st} is the full fishing mortality in sub-area s in year t, then F_{srt} is calculated through gear selection function $p(h_r)$ with h_r denoting the average shell height of scallops in the r-th category.

$$F_{srt} = F_{st}.\ p(h_r). \tag{6}$$

The scallop population after one year is:

$$\begin{aligned} V_{s(t+1)} &= V_{st'}(.*)([e^{-F_{s1t}},\ e^{-F_{s2t}},\ \ldots, e^{-F_{sNt}}])\} \\ &= e^{-M}[G_s].[n_{s1t}.e^{-F_{s1t}},\ n_{s2t}.e^{-F_{s2t}}, \ldots,\ n_{sNt}.e^{-F_{sNt}}] \end{aligned} \tag{7}$$

where (.*) operator is *element-to-element multiplication* of two vectors.

The recruitment vector R is added into the population vector, before the simulation moves forward to the following year:

$$V_{s(t+1)} = V_{s(t+1)} + R_{st}. \tag{8}$$

The number of scallops caught in sub-area s in year t is represented by vector C_{st}:

$$\begin{aligned} C_{st} &= V_{st}(.*)\left[\frac{F_{s1t}}{M+F_{s1t}}(1-e^{-M-F_{s1t}}), \ldots, \frac{F_{sNt}}{M+F_{sNt}}(1-e^{-M-F_{sNt}})\right] \\ &= \left[n_{s1t}\frac{F_{s1t}}{M+F_{s1t}}(1-e^{-M-F_{s1t}}),\ \ldots\ , n_{sNt}\frac{F_{sNt}}{M+F_{sNt}}(1-e^{-M-F_{sNt}})\right]. \end{aligned} \tag{9}$$

The number of scallops harvested are converted into yields in meat weight:

$$Y_{st} = C_{st}.W_s \tag{10}$$

where $W_s = [\ w_{s1}\ w_{s2} \ldots w_{sN}]$ is a weight vector, representing the average meat weight of scallops in sub-area s in each shell height category.

The total yield over the planning period is:

$$Y = \sum_{t=1}^{T}\sum_{s=1}^{S} Y_{st} \,. \tag{11}$$

4 OPTIMIZATION

4.1 Problem Statement

The goal of this research is to determine an area management policy with the optimal fishing rate in each sub-area in each year of the planning horizon. The optimization problem can be stated as follows.

4.1.1 Objective Function

To maximize total fishing yield over the planning horizon.

4.1.2 Decision Variables

Fishing rates in each sub-area in each year of the planning horizon.

4.1.3 Constraints

(a) The fishing rate at one sub-area in any year cannot excess F_{max1} (0.6); and
(b) The average fishing rate for Georges Bank in any given year cannot excess F_{max2} (0.2).

Genetic Algorithm (GA) was employed to solve this optimization problem. GA is a class of stochastic search techniques inspired by natural evolution. Decision variables are encoded as chromosomes. The search process takes place by selection, crossover and mutation operations (Goldberg 1989).

By manipulating encoded chromosomes rather than variables directly, GA can consider non-numerical and qualitative decision variables.

4.2 Simulation Based Optimization

The fishery system we try to optimize contains a great deal of stochastic factors and the objective function is not analytically formulated. During GA's search process, simulation is used to return the objective function's value for each alternative. The approach is therefore called simulation based optimization (Azadivar 1992, Azadivar 1999, Azadivar and Tompkins 1999).

4.3 Genetic Algorithm Implementation

4.3.1 Chromosome Representation

In a Genetic Algorithm process a chromosome (or genome) is a representation of one alternative. Originally, chromosomes are fixed length strings of bits. Koza (1992) introduced a variant of GA, named Genetic Programming (GP). In GP variable size tree structures have been widely used since the tree structures can properly represent a computer program's code.

4.3.2 Selection

The selection operation picks the best chromosomes in the current generation to be transferred into the next generation. One principle in GA is that no matter how poor an individual is, it always has a chance to survive to the next generation. Selection operation therefore must be a probabilistic process. We used ranking selection. Individuals are ranked based on their fitness. Survival probability of one individual is proportional to its rank, regardless of absolute differences in fitness values.

4.3.3 Crossover

A Crossover is the predominant operator in GA and is applied about 90% of the time. According to Holland's building-block hypothesis (in Koza 1992), a good building block (a segment of genome) may be combined into ever better building blocks to form better individuals through the crossover operation.

4.3.4 Mutation

Mutation is usually used with a small probability (1%-5%) in GA. One node of a tree is picked randomly and some information from the node is changed to create a new chromosome.

4.3.5 Handling Constraints

There are several ways to handle constraints within GA (see Michalewicz 1996). In this study, constraints (a) can be checked when a new chromosome is created but constraint (b) cannot. The average fishing rate in Georges Bank is a weighted average. Weight factors are the numbers of scallops in sub-areas. Those numbers in year t are not known until the simulation for year (t-1) is completed. Therefore, the only way to check the constraint is to run simulation. After the simulation for year t finishes, the constraint is checked. If the constraint was violated, there are two options: either stop the simulation and return zeros or adjust the fishing rates to maintain feasibility and continue the simulation. The latter proved to be more sufficient.

5 COMPUTATIONAL RESULTS

The simulation was written in MATLAB because of its ability to manipulate large-scale matrices. The Genetic Algorithm was written in C and integrated into the MATLAB simulation. Inputs for the simulation were obtained from thirteen video surveys in 1999, 2000 and 2001. For the areas the video survey did not sample, we used dredge survey data from NMFS 2000. A dredge efficiency of 25% was used to estimated scallop abundance on the sea floor, based on comparisons between the video survey and the dredge survey Recruitment data from 1979 to 2000 was from the SAFE report (2000).

5.1 Simulation Validation

The 510 km^2 Northeastern portion of Nantucket Lightship Closed Area has been surveyed three years in a row (Aug, 1999-2001) at the same locations with the same number of stations. This provides a unique opportunity to validate the simulation model.

The number of scallops in the area in 1999 was estimated at 217 millions. According to the simulation, that number for 2001 should be 326 millions while the 2001 survey showed there were about 320 million scallop at that time. The simulation projections for shell height frequency of scallop population in the area in 2000 and 2001 are as in Figure 2, that shows the simulation matches reality well.

5.2 Simulation Results

The first simulation run was for the whole Georges Bank at Status Quo, i.e. the closed areas are not allowed to

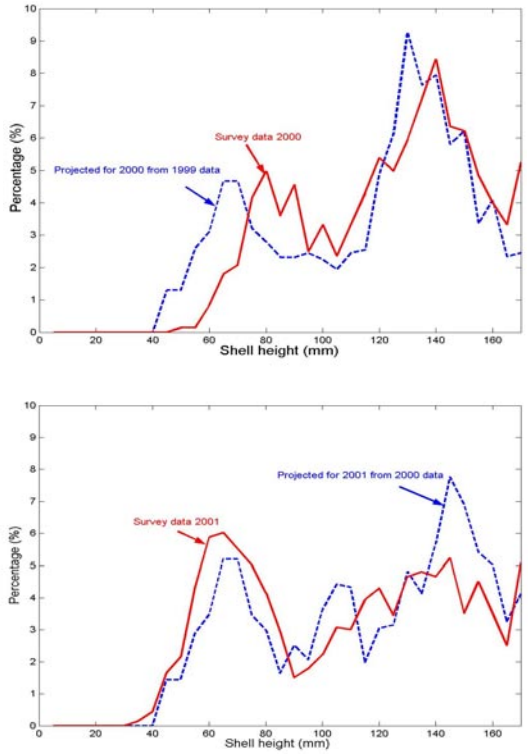

Figure 2. Comparison of Shell Height Frequency From the Simulation Projection and Survey Data for NLSA in 2000 (Above) and 2001 (Below)

Table 1: Simulation Results For 2002 - 2006

Year	Weighted average F_{avg}	Fishing yield in simulation (MT)
2002	0.2	6,102
2003	0.2	5,888
2004	0.2	5,815
2005	0.2	5,831
2006	0.2	5,869
Total		29,505

be fished (F=0); consequently the open areas are allowed to be fished at higher rates so that the weighted average fishing rate $F_{avg} = 0.2$ each year.

Table 2 shows the results from the second simulation run conducted for the hypothetical situation in which closed areas are opened for fishing from 2002 onward. Fishing rates F=0.2 are then applied at any location in Georges Bank.

Table 2: Simulation Results For 2002 - 2006

Year	Weighted average F_{avg}	Fishing yield in simulation (MT)
2002	0.2	13,287
2003	0.2	13,751
2004	0.2	14,349
2005	0.2	15,107
2006	0.2	15,045
Total		71,639

5.3 Optimization Results

The search space is large as all decision variables are continuous. To reduce the size of the search space, we ran simulations for 5 years and for 6 sub-areas. Georges Bank was divided into 6 sub-areas; each covering at least 6% of the historic scallop fishing ground (shaded area) as shown in Figure 3. Decision variables were discrete with an increment of 0.05 for fishing rates. For each alternative, three simulation runs were made and the responses were averaged.

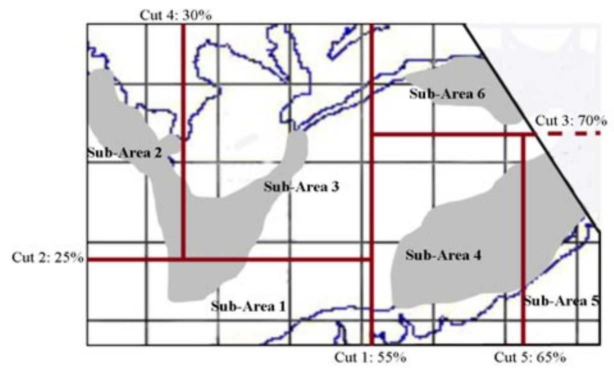

Figure 3: Georges Bank Partition Used in Optimization

Parameters for GA used in our work are shown in Table 3.

Table 3: Parameter For Genetic Algorithm Procedure

Description	Parameter	Value
Population size	PZ	100
Crossover rate	CR	0.55
Mutation rate	MR	0.05
% of reproduction	%R	0.4
% of new replacement	%T	0.6
The number of generations	GE	50

The results in Figure 4 show that the improvement slowed down in the last 15 generations. Averages of populations gradually increase during evolutionary process. but are still far from prematurely converging due to diversity.

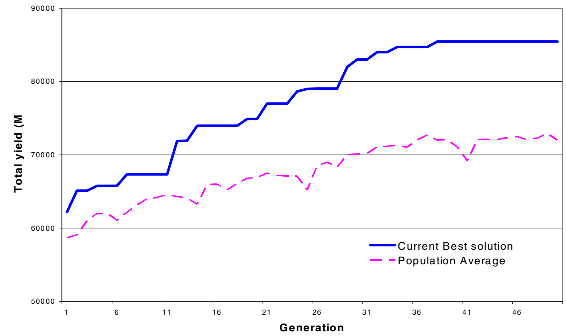

Figure 4: Genetic Algorithm Search Results

The best solution found after 38 generations is as follows:

Table 4: Fishing Rates For Each Sub-area In 5 Years

Sub area	2002	2003	2004	2005	2006
1	0	0	0.6	0	0.6
2	0.25	0.3	0.15	0.1	0
3	0.45	0.3	0.2	0.0	0.5
4	0	0	0.3	0.25	0
5	0.2	0.3	0	0.4	0.1
6	0.35	0.4	0	0.6	0.1

The total yields over five years was 85,475 MT of scallop meat.

In comparison to fishing policies that may yield 58,710 metric tons as an average of 100 alternatives randomly created in the first generation, the best solution increases the total yield by 46%; in comparison to the uniformly distributed fishing policy (Section 5.2).The optimal solution found improves the yield by 19%.

6 CONCLUSIONS

The combination of simulation and optimization techniques provided a powerful methodology for estimating the population dynamics of the sea scallop population of Georges Bank, setting of policies for fishery management and estimating the optimal yield that could be harvested from that resource. The optimal approach was compared to other management strategies and this provided a means to measure the effectiveness of these approaches. The results, however, depend on the quality of the data and biological model used for building the simulation. The data used in this model are the most recent and reliable data collected for this purpose. Further research will focus on improving the biological information on spatial and temporal scales, examining the stock-recruitment relationship, and expanding the optimization modeling effort.

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AUTHOR BIOGRAPHIES

FARHAD AZADIVAR is the Dean of College of Engineering, University of Massachusetts Dartmouth. His areas of research are in modeling and optimization of manufacturing systems, traffic and transportation and management of technological innovation. He is a member of INFORMS and IIE. His e-mail address is <fazadivar@umassd.edu>.

TU TRUONG is a Doctoral Candidate in Operations Research in Industrial and Manufacturing Systems Engineering Department at Kansas State University. His research interests include computer simulation, optimization, inventory control, supply chain design and fisheries management. His e-mail address is <truongtu@ksu.edu>.

KEVIN D.E. STOKESBURY is an Assistant Professor at the School for Marine Science and Technology, University of Massachusetts Dartmouth. His research is in Marine Ecology and Fisheries Science determining the spatial distributions of vertebrates and invertebrates, how they vary temporally, on different scales (km, m and cm), in different environmental conditions and how these variations effect community structure and population dynamics. His recent work focuses on the Georges Bank scallop resource. His e-mail address is <kstokesbury@umassd.edu>.

BRIAN J. ROTHSCHILD is Dean of the University of Massachusetts Graduate School of Marine Science and Technology. His research involves Population dynamics, physical-biological interactions in the oceans, fisheries management, and natural resources policy. His e-mail address is <brothschild@umassd.edu>.