DESIGNING MANAGEMENT ALTERNATIVES FOR THE U.S. ATLANTIC SEA SCALLOP FISHERY: POTENTIAL CONTRIBUTION OF STOCK ENHANCEMENT PROGRAMS AND ROTATION OF FISHING AREAS

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ABSTRACT

Atlantic Sea scallops have historically supported the second most valuable fishery in the northeastern United States. Intense fishing pressure during the early 1990s led to drastic decreases in population biomass and commercial landings. Total harvest, which exceeded 17,000 metric tons (MT) in 1990, declined to around 7,300 MT in 1993. Nevertheless, favorable recruitment events coupled with severe management regulations, including reductions in fishing days and the demarcation of closed areas with restricted access, have promoted a notable recovery of the resource in the last few years. The decline and subsequent recovery of the fishery has stimulated interest on management options such as stock enhancement and rotational fishing as logical extensions to the controlled-access programs currently in place. In this study, a bioeconomic model of the of the sea scallop fishery was constructed to determine the potential benefits of 1) a hatchery-based stock enhancement program, and 2) management of closed areas through rotational fishing. Results of the model indicate that enhancement would provide a much needed buffer against fluctuations of the natural stock; however, an effective enhancement program would require the development of a hatchery infrastructure that is yet not in place. In contrast, rotation of fishing areas represents a much simpler mechanism towards improved management of the scallop resource. Specifically, it is shown that much of the negative impact on the fleet caused by the closure of groundfish areas during the 1990s could have been mitigated by the demarcation of and controlled access to rotational fishing areas.

Keywords: sea scallops; enhancement; rotational management; Georges Bank; Mid-Atlantic Bight

INTRODUCTION

The Atlantic sea scallop, *Placopecten magellanicus*, is a bivalve mollusk that occurs on the eastern North American continental shelf. In the U.S., major aggregations occur in the Mid-Atlantic from Virginia to Long Island, on Georges Bank, in the Great South Channel, and in the Gulf of Maine [1]. U.S. meat landings in 2003 reached the record quantity of 25,100 metric tons (MT), with an ex-vessel value of over $226 million, making the sea scallop fishery the second most valuable in the northeastern United States.

Landings from the U.S. fishery have been rather variable over the years (Fig. 1). Poor recruitment and excessive fishing pressure led to a dramatic decline in commercial landings (below 8,000 MT) during 1993 and 1994. Roughly one-half of the productive scallop grounds on Georges Bank were closed in December 1994 and a myriad of effort-reduction measures have been implemented since then. Scallop biomass quickly rebuilt in the closed areas; it is estimated that over 80% of the sea scallop biomass in the U.S. portion of Georges Bank is now in the areas closed to fishing [1]. Two areas were also closed in the Mid-Atlantic between 1998 and 2001, and a controlled-access program has been operating in these two areas since 2001. Portions of the Georges Bank closed areas were also opened for limited scallop fishing during 1999-2001.

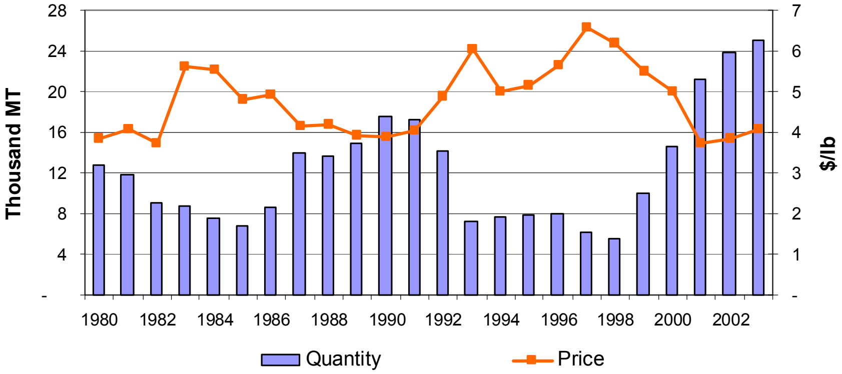


Figure 1. U.S. landings and average ex-vessel price of sea scallops.

The depleted condition of the resource during the early 1990s stimulated interest on scallop enhancement as a viable means to increase fishery yields and protect the natural stocks. Scallop enhancement has evolved to become an integral part of resource management in countries such as Japan, New Zealand, and France [2]. A government-supported demonstration project (The Seastead Project) was conducted in U.S. federal waters between 1995 and 1998 with mixed results. While direct bottom-seeding of juvenile scallops appeared to be economically feasible, culture in various cage structures generated negative returns [3, 4]. The project leaders concluded that, despite the obvious importance of scallop enhancement for the future of the U.S. scallop fishery, excessive regulatory zeal, an unclear legislation framework, and conflicts with fishermen groups remain as major obstacles for enhancement and aquaculture activities in U.S. offshore waters.

The landings of large quantities of scallops from the re-opened areas in Georges Bank during 1999-2001 pointed out the benefits of a rotational system of closed areas. In fact, Amendment 10 of the Atlantic Sea Scallop Fishery Management Plan outlined the characteristics of a rotational closure program to be initiated in Georges Bank and the Mid-Atlantic region in the summer of 2004 [5]. The concept in its simple form is that areas containing beds of small sea scallops are closed before the scallops begin experiencing fishing mortality and then the areas re-open for fishing when the scallops are larger, boosting meat yield.

In practice, this simple concept will prove difficult to apply because it will require consideration of the smallest practical areas to close, the duration of the closures, and the fishing mortality to be applied when the areas re-open. Despite these difficulties, the New England Fishery Management Council (NEFMC) has proposed a fully-adaptive rotation system of flexible-boundary areas. Based on the results from government- and industry-supported resource surveys, the NEFMC would consider areas for closure when the expected increase in exploitable biomass in the absence of fishing mortality exceeds 30% per year, and re-open to fishing when the annual biomass increase in the absence of fishing mortality is less than 15% per year. This strategy would protect areas with young, fast-growing scallops, and re-direct fishing pressure to areas with older, slower growing scallops. The NEFMC has proposed to use ten-minute squares (each about 75 square nautical miles) as the basis for the evaluation of contiguous blocks that may close to protect young scallops. A ten-minute square implies a level of micro-management that is currently not possible to achieve with the existing government surveys. It is still unclear whether industry-supported surveys will provide sufficient information for implementation of this fully-adaptive rotation system.

Given the potential benefits that could be derived from stock enhancement and rotation of area closures, the goal of this study is to conduct a comparative analysis of these management options relative to the "status quo" management system based on static closure areas with temporary access programs. The study develops an age-structured population dynamics model that simulates the evolution of scallop stocks in various management regions reflecting the effects of natural processes (recruitment, natural mortality) and fishery management decisions on stock biomass and the level of commercial landings. The model was used to develop estimates of the net revenues that could be generated by 1) a stock enhancement program supported by a system of hatcheries in the northeast and mid-Atlantic regions, and 2) a simplified rotational management system for the closed areas in Georges Bank. Results of this study will provide us with an assessment of the potential gains to be realized with each management alternative, thereby contributing to our knowledge base for improved management of the Atlantic sea scallop resource.

METHODS

Our modeling approach is similar to that used in population dynamics models developed by biologists at the Northeast Fisheries Science Center, National Marine Fisheries Service (NEFSC/NMFS) [6, 7]. These models have been successful in forecasting the increases in sea scallop abundance, landings, and catch rates that have been observed in the last several years. For our purposes, the Georges Bank (GB) and Mid-Atlantic Bight (MAB) stock areas are sub-divided in 11 management sub-regions: seven in GB (four closed areas and three open areas) and four in the MAB (two closed areas and two open areas). Table I lists the management sub-regions and their respective areas in square nautical miles (nm^2) [8].

Table I. Management Sub-regions in the Georges Bank and Mid-Atlantic Bight Stock Areas

		Name	Area (nm^2)
Georges Bank	Closed Areas	Closed Area I	673
		Closed Area II – Northern Part	863
		Closed Area II – Southern Part	994
		Nantucket Light Ship Closed Area	828
	Open Areas	North Edge and Peak Open Area	989
		South Channel Open Area	1,373
		Southeast Part Open Area	1,562
Mid Atlantic Bight	Closed Areas	Hudson Canyon South Closed Area	1,461
		Virginia Beach Closed Area	130
	Open Areas	Delmarva Open Area	1,411
		New York Bight Open Area	5,356

The model uses a difference equation approach where time is partitioned into discrete time steps t_1, t_2, …, with a time step of length $\Delta t = t_{k+1} - t_k = 0.042$ years (approximately 14 days). Population is tracked in each management sub-region i and time t by population vectors $\mathbf{p}(i,t) = (p_1, p_2, \ldots, p_n)$, where p_j represents the density of scallops in the j^{th} size class in region i at time t. Catches at each size class in the i^{th} region and k^{th} time step are represented by a landings vector $\mathbf{h}(i, t_k)$ calculated as

$$h(i,t_k) = [I - e^{(\Delta t H(i,t_k))}]p(i,t_k) \quad \text{(Eq. 1)}$$

where I is the identity matrix and H is a diagonal matrix whose j^{th} diagonal entry h_{jj} is given by

$$h_{jj} = \begin{cases} 0 & \text{if } s(j) \le s_d \\ -F_c(i,t_k)\dfrac{[s(j) - s_{\min}]}{(s_{full} - s_{\min})} & \text{if } s_d < s(j) < s_{full} \\ -F_c(i,t_k) & \text{if } s(j) \ge s_{full} \end{cases} \qquad \text{(Eq. 2)}$$

where $s_{\min}$ is the minimum size at which a scallop is vulnerable to the gear, s_{full} is the size at which a scallop is fully vulnerable to the gear, s_d is the cull size ($\geq s_{min}$) below which scallops are discarded, and F_c (i, t_k) denotes the capture fishing mortality rate suffered by a full recruit in area i at time t_k.[6].

Shell-height-meat-weight conversion parameters are used to estimate the vector of meat weights $\mathbf{m}(i)$. The landings $L(i, t_k)$ for the i^{th} region and k^{th} time step are calculated using the equation

$$L(i,t_k) = A_i\, \mathbf{h}(i,t_k) \bullet \frac{\mathbf{m}(i)}{(we_i)} \qquad \text{(Eq. 3)}$$

where A_i and e_i represent the area and dredge efficiency in the i^{th} region, respectively, and w is the tow path area of the survey dredge.

Scallops of shell height less than a minimum size s_d are assumed to be discarded and suffer a discard mortality rate of d (20%). Some scallops not actually landed may suffer mortality due to incidental damage from the dredge. Incidental fishing mortality was modeled as $F_I = 0.175\ F_c$ in Georges Bank and as $F_I = 0.03\ F_c$ in the Mid-Atlantic regions [7].

The scallops grow according to a Von Bertalanffy equation so that their shell height $s(t)$ at age t (in years) is given by

$$s(t) = L_\infty [1 - e^{(-k[t-t_0])}] \qquad \text{(Eq. 4)}$$

Equation (4) can be used to construct a matrix G, which specifies the fractions of each size class that remains in that size class, or grows to other size classes, in a time $\Delta\ t$. The population dynamics of scallops in each size class can be summarized in the equation

$$p(i,t_{k+1}) = \rho_i + G\ e^{(-MH)\Delta t}\, p(i,t_k) \qquad \text{(Eq. 5)}$$

where ρ_i denotes recruitment into the j^{th} size class at time t and M is a matrix containing the natural mortality, discard fishing mortality, and incidental fishing mortality parameters. The population and harvest vectors are converted into biomass by using the shell-height meat-weight relationship:

$$W = e^{[a+b\ln(s)]} \qquad \text{(Eq. 6)}$$

where W is the meat weight of a scallop of shell height s. Commercial landing rates (LPUE) were estimated using an empirical function based on the observed relationship between annual landing rates and survey exploitable numbers per tow [7]. A modified Holling Type-II model was used so that the landings per unit of effort (number of scallops landed per day at sea) L will depend on scallop exploitable biomass B according to the formula:

$$L = \frac{\alpha\, B}{\sqrt{\beta^2 + B^2}} \qquad \text{(Eq. 7)}$$

The parameters α and β need to be modified according to crew size. Starting in 1994, the maximum crew size allowed in scallop vessels was seven men. Before then, an average scallop vessel would have a crew of 9-10 men. Table 2 summarizes all model parameters.

Table 2. Parameters of the Age-structured Model for Atlantic Sea Scallops in Georges Bank and the Mid-Atlantic Bight Stock Areas

Parameter	Description	Value
Δt	Simulation time step	0.042 years
L_∞	Maximum shell height	152.46 mm (GB), 151.84 (MAB)
K	Growth parameter	0.4 y^{-1} (GB), 0.23 y^{-1} (MAB)
m	Natural mortality rate	0.1 y^{-1} across all size classes
a	Shell height/meat weight parameter	-11.6038 (GB), -12.2484 (MAB)
b	Shell height/meat weight parameter	3.1221 (GB), 3.2641 (MAB)
s_0	Initial shell height of recruit	40 mm
s_{min}	Minimum size retained by gear	65 mm
s_{full}	Size for full retention by gear	90 mm
s_d	Maximum size discarded	80 mm
d	Mortality of discards	0.2
e	Dredge efficiency	0.5 (GB), 0.7 (MAB)
α	LPUE/biomass relationship (seven-man crew)	49,056
β	LPUE/biomass relationship (seven-man crew)	102.8

Status Quo Management

A *status quo* scenario was developed by recreating the conditions of the fishery during the period 1990-1999. The Northeast Fisheries Science Center (NEFSC/NMFS) conducts periodic assessments of the sea scallop population in U.S. federal waters through Stock Assessment Workshops (SAW). The 32nd SAW report (2001) compiled the results from the annual government-supported surveys and provided a complete overview of the status of the resource in each management sub-region between 1979 and 2000 [8]. The annual surveys provide complete estimates of biomass, population numbers, and length frequencies. Information from the 1990 survey was used to establish initial conditions for the age-structured model. Because the surveys describe the status of the resource at the beginning and end of each year, the capture fishing mortality rate $F_c\,(i, t_k)$ and the recruitment rate ρ_i in the population model were adjusted so that the number of individuals and distribution by size classes predicted by the model coincided with the results from the annual surveys. It should be noted that the biological surveys are subject to sampling variability, thus the derived estimates can not be interpreted as exact measures of fishing pressure and recruitment events. However, these estimates do reflect stock trends and provide an adequate characterization of a *status quo* management scenario that can be used for further comparisons with other management alternatives.

Economic Sub-model

The population dynamics model predicts annual landings for the entire fishing fleet, therefore its was necessary to develop ex-vessel price equations to describe the interactions between ex-vessel price, the level of domestic landings, and other price determinants such as disposable income per capita and price and quantity of scallop imports. Monthly landings data (1998-2003) provided by the NEFSC/NMFS were used to develop price equations for six different size categories (under 10, 11-20, 21-30, 31-40, 41-50, and 61+ counts). Upon examination of alternative models, ex-vessel price of sea scallops in each size category was postulated to be a function of domestic landings and average price of all imports of Canadian scallops to the northeast region. For brevity reasons, the price equations are not presented here.

Specification and estimation of cost equations are also necessary for analyzing policy options. A cost equation developed by the NEFSC/NMFS was used to estimate annual operating costs of scallop fishing (*OPC*) as a function of vessel crew size (*CREW*), vessel size in gross tons (*GRT*), and vessel days at sea (*DAS*) [7]. The equation is

$$\underset{(6.31)}{Log\ (OPC) = 4.6130} + \underset{(3.34)}{0.2531} * Log\ (CREW) + \underset{(3.46)}{0.2743} * Log\ (GRT) + \underset{(8.79)}{1.1134} * Log\ (DAS) \quad \text{(Eq. 8)}$$

n = 69, adj R-sq = 0.58, D-W = 1.97, t-value in parentheses.

Stock Enhancement Program

Stock enhancement in Japan is mostly done through collection of wild spat and bottom re-seeding in protected bays. The government-funded Seastead Project relied on collection of juvenile scallops in the groundfish closed areas to re-seed the growout locations. Given our incomplete knowledge of “hot spots” collection areas and the inherent variability of wild spat abundance, it appears that a large-scale enhancement program conducted in U.S. federal waters would have to depend on hatchery-supplied seed. That has been the case in places such as the Bay of Brest in France, where hatchery production contributes a significant portion of landings from the scallop fishery [9].

The stock enhancement scenario assumes that a system of hatcheries is in place to support enhancement activities in Georges Bank and the Mid-Atlantic Bight. Five hatcheries in each stock area with an individual production capacity of 100 million juveniles per year (shell height of 25 mm) would meet the seeding requirements for approximately 14.58 nm^2 at a stocking density of 10 juveniles/m^2. Assuming a growout cycle of five years and rotation of seeded areas, the total area allocated for the enhancement program would be nearly 73 nm^2 (14.58 nm^2 *5) in both Georges Bank and the Mid-Atlantic Bight. The five seeding areas would be initially stocked between 1990 and 1994, with the first harvest occurring in 1995 (corresponding to the area seeded in 1990). The model assumes annual harvests until the end of the modeling period, in 1999. Additional simulations of this scenario were run assuming growout cycles of 3 and 5 years.

The enhancement program is assumed to take place in any of the closed areas in GB and the MAB. Harvesting of seeded areas would be done through a cooperative agreement among fishermen. The cost of the enhancement program is mostly limited to the purchase of hatchery seed ($0.02 per seed) [10].

Rotational Management of Closed Areas

The last scenario proposes a simple rotation scheme for the groundfish closed areas in Georges Bank. It is assumed that the areas are closed in January 1990 (rather than December 1994) and each area is sub-divided in four equal sections. Every year one of the sections in each area is re-opened for fishing (F_c = 0.32). Rotation takes place between 1990 and 1999. It is assumed that fishing activity within the re-opened sections does not affect recruitment in the surrounding areas.

In practice, it may be difficult to implement such a rotation system given that the closed areas are also governed by regulations pertaining to other species. This practicality was overlooked since the purpose of the analysis was simply to demonstrate the potential benefits associated with rotational fishing.

RESULTS

Figure 2 compares the gross revenue predicted by the *status quo* management scenario with the actual revenue from the fishery, as reported by NMFS [11]. Despite the uncertainties and sampling variability associated with the resource surveys, the age-structured model reflects to a considerable extent the major trends in domestic landings. Gross revenue from the fishery was in the proximity of $150 million during 1990-1992. Poor recruitment caused in part by overfishing translated into a significant decline in landings in 1993 and 1994. Gross revenue did not exceed $100 million between 1995 and 1998 given the overfished condition of the resource and the exclusion of vessels from the closed areas in GB. The surge in landings (see Fig. 1) and revenue in 1999 was due to the temporary re-opening of GB CLII-S. Gross revenue predicted by the model in 1998 and 1999 was lower than what was observed because the survey data suggested unusually low fishing mortalities in the Mid-Atlantic region in those particular years.

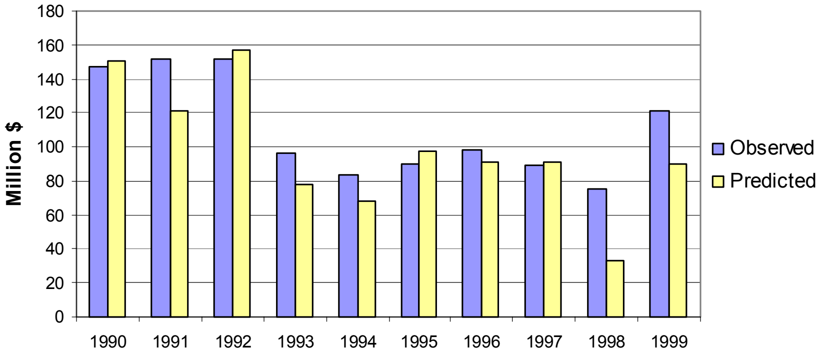


Figure 2. Observed and Predicted Gross Revenues for the U.S. Atlantic Sea Scallop Fishery

Stock Enhancement Program

Table 3 summarizes the results of the stock enhancement scenario. Net Present Value (computed with respect to 1990 at a discount rate of 7%) of the stream of annual revenues (net of operating costs) between 1990 and 1999 would be highest for the four-year growout cycle (near $560 million). Assuming a recovery rate (i.e., dredge efficiency) of 50 and 70% in GB and MAB (see Table 2), annual harvest from the ranched areas would be 2,138 and 1,442 MT, respectively. Production would be greater in GB because of the superior growth rates (Table 2). Comparatively, the estimated NPV for the *status quo* management scenario was $503,672,250.

Table 3. Results from the Stock Enhancement Scenario

	3-year cycle		4-year cycle		5-year cycle	
	GB	MAB	GB	MAB	GB	MAB
Annual production from ranched areas (MT)	1,571	939	2,138	1,442	2,474	1,882
Size count (#/lb)	11-20 & 21-30	31-40 & 41-50	11-20	21-30 & 31-40	11-20	11-20 & 21-30
Number of harvests in 10 years	7		6		5	
NPV (10 years, 7%)	$511,303,447		$555,808,909		$553,665,185	

Figure 3 shows the relative contribution of enhancement to the total quantity harvested by the fishery. Enhancement represented between 30-40% of total landings during 1993-1999, years during which natural recruitment in the fishery was particularly low. An enhancement program has also the potential to reduce the economic impact on the fleet caused by the closure of some of the most productive areas.

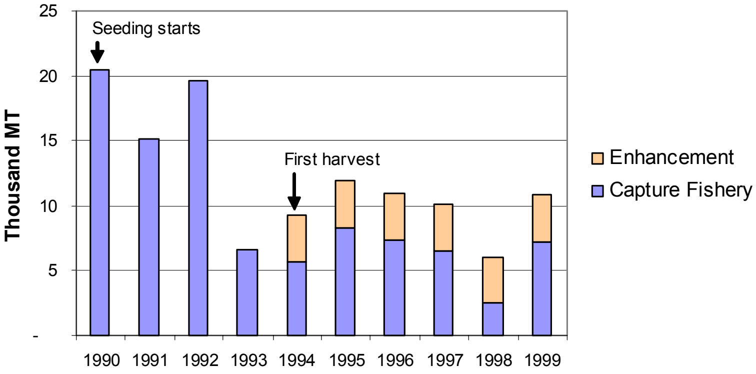


Figure 3. Relative contribution of enhancement to total landings from the Atlantic sea scallop fishery (1990-1999). Growout cycle of cultured scallops is four years.

Rotational Management of Closed Areas

Although landings during 1990-1992 significantly decreased as compared to the *status quo* scenario, rotational harvesting of the groundfish closed areas resulted in increased yields in the years thereafter (Fig. 4). The estimated NPV for the rotational management scenario was $614,366,072, i.e., 22% higher than the *status quo*.

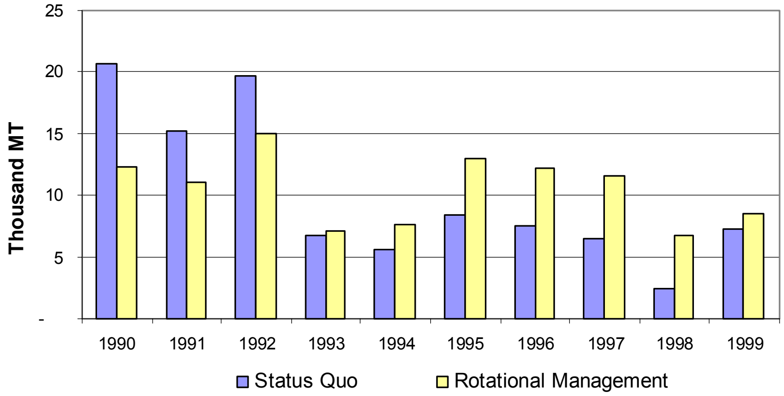


Figure 4. Total landings from the Atlantic sea scallop fishery under *status quo* management and rotational harvesting of groundfish closed areas.

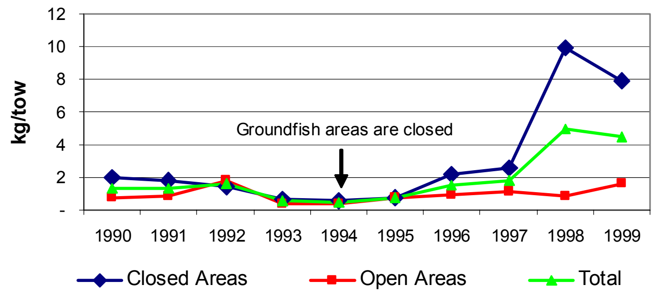
As with the network of closures, rotational management leads to rapid increases in the biomass of scallops in the protected areas (Fig. 5). If closures had taken place in 1990, biomass within the closed areas in GB might have reached 18 kg/tow by 1998, i.e., 80% higher than in the *status quo* scenario.

DISCUSSION

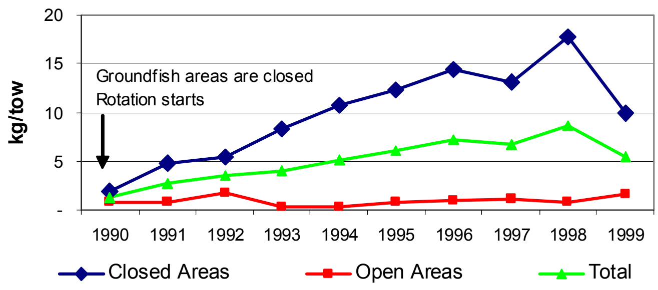
Stock Enhancement Program

Scallop enhancement techniques have been developed over the years to the extent that sea ranching programs contribute a significant portion of fishery landings in countries such as Japan, France, and New Zealand. Scallop aquaculture in North America is still in the initial stages of development with the most important accomplishments in hatchery and growout technologies having occurred primarily in Canada [10]. Enhancement programs have been successful in Japan because highly efficient techniques have been developed for collection of wild spat and because the costal topography in the fishing regions provide sufficient protected locations for the deployment of culture structures. In contrast, the most productive areas in the U.S. are found in offshore locations subject to strong currents and harsh weather conditions during the winter months. Researchers from the Seastead Project reported severe damage to some of their cage and buoy structures due to the strong currents in the area (in some instances, damage was also inflicted by vandals) [3].

At present, it appears that bottom-seeding of juvenile scallops in “reserve” areas is the only feasible form of scallop aquaculture in U.S. offshore waters. Still, this approach would be dependent on a consistent supply of hatchery-produced seed. Scallop hatchery technology in North America is still evolving. Some important breakthroughs have been achieved at facilities in Martha’s Vineyard (Massachusetts) [12], but hatchery technology is more advanced in Canada. Currently, there are operating hatcheries in Newfoundland with a production capacity of 20 million scallops per year [13].



a) *Status Quo*



b) Rotational management

Figure 5. Biomass of Atlantic sea scallops in closed and open areas of Georges Bank: a) *Status Quo* scenario; b) Rotational management of groundfish closed areas.

The enhancement scenario in our model assumed a hatchery production capability that is not yet existent in the U.S (1 billion 25-mm seed per year). However, provided there were a sufficient degree of commitment on part of the government and the private sector, such production capability could be potentially developed. Our results show that enhancement activities would yield on average about 3,580 MT per year, assuming a 4-year growout cycle. Average landings between 1980 and 2003 were 12,253 MT (Fig. 1), therefore enhancement could potentially contribute on average about 23% of the total fishery yield. Unlike the wild-based fishery, production from the enhanced areas would be much more stable, removing the uncertainty associated with natural recruitment.

Despite our projections, it is unlikely that scallop enhancement becomes an essential component of fishery management in the U.S. to the extent it has in places such as the Bay of Brest in France or the Southern Scallop Fishery in New Zealand. This is in part because these fisheries are relatively small, with annual yields ranging between 150-350 MT in France and 400-700 MT in New Zealand [9, 14]. The associated fishing communities are also small, which among other things facilitates coordination for seeding and harvesting of the common grounds.

Finally, the 10-year NPV estimate for the 4-year grow-out cycle was slightly higher than for the 5-year cycle. This difference was mainly due to the relatively short time period considered for the analysis, i.e, it does not necessarily mean that it is more advantageous to harvest a greater number of 4-year scallops as compared to a smaller number of larger 5-year scallops. If the analysis were expanded to 20 years, the difference in NPV would be negligible. In contrast, harvest value is lower if the growout cycle is limited to three years.

Rotational Management

The most interesting result from the analysis was that overall landings from the closed areas in Georges Bank were greater under rotational management as compared to *status quo* management even when the available fishing area was much smaller under the former scenario. In concrete numbers, the comparison is as follows: under *status quo* management, total area available for fishing in the closed areas between 1990 and 1999 was approximately 16,790 nm^2 (the four closed areas add up to 3,358 nm^2 and were open for five years between 1990 and 1994). Under rotational management, 25% of the closed areas was available for fishing every year between 1990 and 1999, therefore total fished area in the 10 years was 8,395 nm^2. Despite this disparity, total landings (all areas in GB and MIB) in the 10 years under *status quo* management was 99,977 MT while landings amounted to 105,038 MT in the rotational fishing scenario.

Figure 5 suggests an explanation to this result: the closed areas were heavily fished during 1990-1994 even though biomass was very low (less than 2 kg/tow). Under these conditions, landings remained low while the cost of fishing increased. Under rotational management, access to the scallop beds was granted only until biomass had been rebuilt, which made fishing much more efficient. Harvests that were missed in the previous three years were rapidly captured during the re-opening periods.

Rotation of fishing areas appears as a simple yet effective method to rationalize fishing effort in the scallop fishery. It re-directs fishing pressure in a manner that is much more consistent with the biological characteristics of the resource. There is little doubt that the fishery will benefit from the recent shift in management towards rotational harvesting of fishing grounds. On the other hand, the adaptive approach with flexible-boundary areas recommended by the New England Fishery Management Council (NEFMC) will probably demand more information than what the biological surveys will be able to provide. Also, boundaries that are constantly moving may generate some confusion among fishermen. To begin with, rotational management of fishing areas with fixed boundaries would provide more than satisfactory results.

Directions for Future Research

Our analysis poses interesting questions for follow-up studies. For instance, it would be interesting to determine how large the network of closed areas would have to be in order to maximize net revenues in the fishery. Such a study should take into consideration the possible effect of closures on recruitment within and outside the protected areas. Thus far this effect has not been well documented.

Other management schemes should also be considered. In the absence of quotas, cooperative agreements among fishermen may provide a mechanism for rationalization of fishing effort. Harvesters cooperatives may also be useful for acquisition of inputs at reduced prices, reducing the overall cost of fishing. Scallop cooperatives have been relatively successful in New Zealand; it may be time to explore this option for the U.S. fishery.

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