

Integrating spatial management measures into traditional fishery management systems: the case of the Georges Bank multispecies groundfish fishery

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Primary determinants of the productivity of most fisheries are the level of fishing mortality and the age structure of the catch. Constraints on nominal effort or catch and technical measures such as mesh sizes are typically the most effective methods of ensuring productivity and sustainability. Stock assessment models are generally well adapted to assess the biological implications (though less often the economic implications) of these measures. However, the increasing use of spatial management measures such as marine protected areas (MPAs) or seasonal area closures presents new challenges for fishery managers. Assessment models and data collection programs are rarely designed or adaptable for analysis of these measures. Using spatial management measures effectively requires new models and data. Models of Georges Bank groundfish fisheries are presented and used to explore the impacts of area closures in the context of the overall management system. Although the spatial dynamics of the models are highly stylized, they illustrate mechanisms through which area closures can increase productivity and profitability of a spatially heterogeneous multispecies fishery. The utility of taxes to control the distribution of effort is also explored.

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Introduction

Most fisheries management systems rely on a mix of regulatory measures to achieve desired objectives. Controls on catch or effort are commonly supplemented with gear restrictions, size limits, and, increasingly, with spatial and temporal controls on effort. However, assessment tools and data collection programs are often inadequate to determine the expected outcomes from a given mix of management measures. Most fishery assessment models are designed only to make predictions of how changes in fully recruited fishing mortality will impact harvest and biomass levels of individual species. They are not easily adaptable to exploration of the consequences of the changes in total and relative fishing mortality across age classes and species that may result from management measures that shift effort spatially.

Assessing the utility of a particular management tool such as the choice of mesh size or the location of an area closure usually cannot be done in isolation because the biological and

economic effects of one tool are dependent on how other tools are being used. For example, increases in mesh size alter yield-per-recruit isopleths thereby changing the effort level that provides a maximum yield as well as changing the associated harvest costs. Temporal and spatial controls on effort may function in a similar way by changing age or species selectivity and overall catchability. The optimal sizes of mesh and area closures and the optimal level of fishing are likely to be interdependent. To determine an optimal mix of management measures, it is useful to have an assessment tool that allows for concurrent assessment of changes to all or at least the most important management measures in the management system. Design of the appropriate assessment tools will also help guide design of data collection programs.

The need for spatial assessment tools is particularly acute in the groundfish fisheries prosecuted on Georges Bank off the coast of New England. The management system for these fisheries, relies heavily on year round area closures, which were implemented in 1995 as part of a groundfish

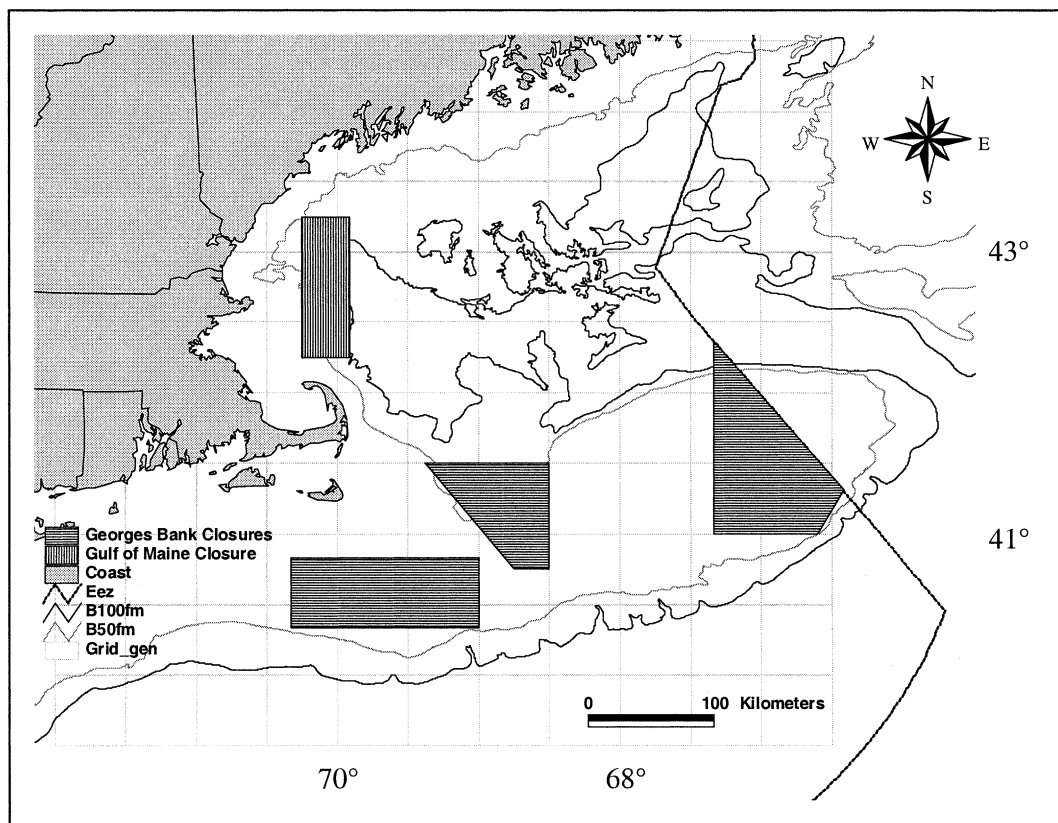


Figure 1. Year round groundfish area closures on Georges Bank.

stock rebuilding plan. The year round area closures on Georges Bank and in the Gulf of Maine are shown in Figure 1. Parts of these areas had been closed seasonally before 1995 to protect spawning aggregations. To the extent these closed areas also had high catch rates the rest of the year (relative to areas left open), fishing mortality from a given level of nominal effort would be reduced immediately by closing them year round. The closures were also expected to allow groundfish stocks to build up inside their boundaries. Over time this would continue to reduce fishing mortality on groundfish stocks by prohibiting fishing in areas with the highest concentrations of fish. Even after rebuilding targets are met, area closures of some form are likely to remain as a means to protect “essential fish habitat”¹ and, potentially, to tune the vector of fishing mortalities in this complex multispecies fishery.

This paper first presents a spatial simulation model of Georges Bank cod (*Gadus morhua*) that is used to assess combinations of nominal effort, mesh size and area

closures. Revenue curves are constructed from the equilibrium yield curves derived from different combinations of mesh sizes and area closures. The model is used to explore the impacts on fishery productivity and profitability of different combinations of mesh sizes and area closures under varying assumptions about spatial heterogeneity and movement of juvenile and adult cod.

While the single species model provides some useful information about the impacts of different management strategies for the cod fishery, it does not provide sufficient information to determine the combination of management measures that will optimize the groundfish fishery profitability in a mixed groundfish fishery. Cod revenues represent only a portion (ranging from 20 to 40% over the last decade) of the value derived from effort applied to the demersal complex of species on Georges Bank and the Gulf of Maine. Depending on the shape of the yield isopleths of the different species in the complex and their relative catchability, the economically optimal level of effort and optimal mesh size may be higher or lower than that suggested by any single species model. The single species model is extended to include two additional stocks, Georges Bank haddock (*Melanogrammus aeglefinus*) and Georges Bank yellowtail flounder (*Limanda ferruginea*). Again the impacts of alternative combinations of effort,

¹The 1996 Magnuson–Stevens Fishery Conservation and Management Act (MSFCMA) directs fishery managers to: (1) identify and describe essential fish habitat (EFH) in each fishery management plan; (2) minimize to the extent practical the adverse effects of fishing on EFH and (3) identify other actions to encourage the conservation and enhancement of EFH.

mesh size and area closures are explored. An alternative means of influencing the spatial distribution of effort through taxes on cod landings is also explored.

In its current form, this model falls short of providing absolute quantitative management advice on the appropriate levels of effort and mesh size or size and location of area closures for the Georges Bank multispecies groundfish fishery. Inclusion of other important species and more information on the spatial structure and behavior of the fishes and fishers will be necessary. Also, this model only considers the otter trawler portion of the fishery while gillnet and line fisheries also account for a significant portion of groundfish catches, particularly of cod. Nevertheless, the model provides important insights into the relative impacts and utility of different sorts of management measures and helps to identify and prioritize the critical data necessary to parameterize an operational management assessment model for this and other fisheries.

Methods

Base model

Presented below is a one-dimensional, age structured model of Georges Bank cod that allows for spatial heterogeneity in the distribution of fish and effort. A one-dimensional model is sufficient to explore a variety of important questions regarding the usefulness of spatial management measures while introducing considerably less complexity than a two-dimensional model. Georges Bank is represented by a linear arrangement of 51 grid cells. A short time step of 5 days is used to maintain stability of the advection process.

The change in the number of individuals of cohort i in grid cell x is determined by:

$$N_{x,i,t+1} = N_{x,i,t} e^{-Z_{x,i,t}} + \frac{\partial(D_i(\partial N_{x,i,t}/\partial x))}{\partial x} - \frac{\partial(v_{x,t}N_{x,i,t})}{\partial x} \quad (1)$$

where $Z_{x,i,t}$ is the instantaneous total mortality for each cohort, i , in each area, x , D_i the diffusion constant and the advection coefficients $v_{x,t}$ are functions of the gradient of local suitability LS :

$$v_{x,t} = -\frac{\partial(LS_{x,t})}{\partial x} \quad (2)$$

which is a function of the biotic affinity, ba_x , of the species to the location and the density of fish in that location relative to carrying capacity, K_x , which is specified in terms of biomass:

$$LS_{x,t} = -ba_x \left(1 - \frac{\sum_{i=2}^{15} N_{x,i,t} \times wt_{x,i,t}}{K_x} \right) \quad (3)$$

Note that K_x are assumed to be proportional to ba_x so that areas with higher carrying capacity continue to have proportionately higher local suitability and hence immigration

when all areas have the same ratio of biomass density to carrying capacity.² Thus at low levels of abundance, the stock would tend to contract to the most favorable areas. The weight of individuals in each cohort, $w_{x,i,t}$, are updated at each time step based on the published von Bertalanffy length-at-age function and length-weight conversion factors (see Table 1). The model does not track individual fish, only the number and size of fish in each cohort. Weight-at-age changes throughout the year as fish of a given age class get older. Weights-at-age and time are exogenous to the model and homogenous over space. The diffusion-advection scheme used is a variation of one developed by MacCall (1990)³ and adapted by Maury and Gascuel (1997). This scheme is extended to a multicohort fishery which requires addressing the question of whether and how cohorts interact. In the base model it is assumed that the advection gradient for all age-two and older fish is based on total local biomass of those cohorts relative to local carrying capacity. Age-one fish are assumed to behave independently of the adult stock. There is a separate $LS_{x,t}$ for age-one fish which is calculated in the same manner as Equation (3) except that the local biomass and carrying capacity used in calculating $LS_{x,t}$ is for age-one fish only, and the carrying capacity and biotic affinity are assumed to reflect the spatial distribution of recruits which is described later.

Total mortality for each cohort in each area, $Z_{x,i,t}$ is the sum of fishing and natural mortality. Natural mortality is set at an instantaneous rate of $M = 0.20$. Cohort-specific fishing mortality is calculated as

$$F_{x,i,t} = q \times \rho_{i,t} \times E_{x,t} \quad (4)$$

where q is the catchability coefficient, $\rho_{i,t}$ the age-specific partial recruitment for the i th cohort at that point in the year and $E_{x,t}$ is the nominal effort level in vessel days fished in the x th area. The partial recruitment vector, $\rho_{i,t}$, is a function of mesh size and fish length calculated from a meta analysis of several studies (De Alteris and Grogan, 1997) and is calculated as

$$\rho_{i,t} = [1 + e^{\alpha(\text{length} - (\text{SF} \times \text{mesh size}))}]^{-1} \quad (5)$$

where SF is a selection factor specific to the species, gear and shape of mesh. Length is the average length for the age class at time t as determined from the published von Bertalanffy equations (Table 1). Note that only partial recruitment for otter trawl gear is modeled.

²This is not true in the limiting case where all areas are exactly at carrying capacity so that $LS = 0$.

³MacCall provides an extensive discussion of alternative schemes and the ecological basis for choosing this one in the appendix of his book.

Table 1. Growth and recruitment parameters and catchability coefficients for Georges Bank cod, haddock and yellowtail flounder.

Species	von Bertalanffy coefficients ^a $L_t = L_\infty(1 - e^{-K(t-t_0)})$			Length-weight conversion ^b $\ln(W) = \delta + b \times \ln(L)$		Recruitment coefficients $R = \frac{a \times \text{SSB}}{c + \text{SSB}} \times e^{\sigma^2/2}$			Mesh selectivity $\rho_{i,t} = [1 + e^{\alpha(\text{length} - (\text{SF} \times \text{mesh size}))}]^{-1}$	
	L_∞	K	t_0	b	δ	a	c	σ^2	α	SF
Cod	148.1	0.120	-0.616	3.052	-11.723	37.745	95.827	0.240	-0.24	4.09
Haddock	73.8	0.165	0.165	3.068	-11.720	17.106	39.738	1.873	-0.36	3.79
Yellowtail flounder	46.0	0.629	0.676	3.129	-12.071	50.090	10.737	0.420	-0.72	2.02

^avon Bertalanffy parameters cod are from Penttila and Gifford (1976), for haddock are from Clark *et al.* (1982) and for yellowtail flounder from Moseley (1986).

^bRecruitment parameters for haddock and yellowtail flounder are from Overholtz *et al.* (1999).

The Baranov catch equation is used to calculate catch as

$$C_{x,i,t} = N_{x,i,t} \frac{F_{x,i,t}}{Z_{x,i,t}} (1 - e^{-Z_{x,i,t}}) \tag{6}$$

where $C_{x,i}$ is the catch in numbers from the i th cohort in the x th area. Harvest biomass from each cohort for each area and time period, $H_{x,i,t}$, is calculated by multiplying the numbers of individuals caught by their age-specific average weights estimated from the length-at-age function and the length-weight relationship⁴

$$H_{x,i,t} = C_{x,i,t} \times W_{x,i,t} \tag{7}$$

Total revenues for each area and time period are calculated by summing over cohorts the product of the cohort-specific harvest biomass and prices that vary by fish size. Price, $P_{i,t}$, is time subscripted because fish size changes throughout the year so that a fish in a given age class may move to a different market category and price during the year. Size-specific prices are specified exogenously⁵ by using average 1998–2000 prices for cod landed by trawlers in Maine and Massachusetts.⁶

⁴Length and weight-at-age are assumed to be independent of stock size and density. If in fact growth was density dependent, the model might tend to overestimate the benefits of lower fishing mortality and of area closures since growth rates would slow as stock sizes increased or stocks became densely aggregated in closed areas.

⁵While one might expect prices to vary inversely with the level of supply, this may be considerably moderated in the long run by the increasing international integration of whitefish markets. Recent demand models for this fishery are not available at this time and could not be expected to predict prices far in the future. If prices do vary inversely with supply, this tends to reduce the benefits of increased harvests and may reduce the benefits of closures since revenues would not rise as much to offset the higher costs associated with higher effort levels required to achieve given harvest levels with area closures in place.

⁶These prices are derived from mandatory reporting forms supplied by fish buyers to the National Marine Fisheries Service. Prices might also be expected to vary by season and area, but only a size effect is modeled.

$$R_{x,t} = \sum_{i=1}^{15} P_{i,t} \times H_{x,i,t} \tag{8}$$

At the end of each year, recruitment (the number of age-one fish at the beginning of the year) is calculated using a deterministic Beverton and Holt stock–recruitment function (Overholtz *et al.*, 1999) as

$$R = \frac{a \times \text{SSB}}{c + \text{SSB}} \times e^{\sigma^2/2} \tag{9}$$

where SSB is overall spawning-stock biomass at the peak spawning period and a and c are estimated parameters (see Table 1). The estimated variance of the stock–recruitment function is σ^2 and $\sigma^2/2$ is the expected value of the multiplicative residual of the stock–recruitment function. The expected value of recruitment is the product of this residual and the stock–recruitment function. Recruitment in this model is affected only by SSB and may underestimate the impacts of area closures. It has been suggested that area closures may increase the ratio of recruits to spawners by eliminating disturbance of spawners or by limiting pre-recruit mortality, however, this effect has not been documented or quantified and is not modeled here. In the base model, recruits are distributed spatially according to a truncated normal distribution with its mode in the center of the linear grid (see Figure 2a).

Also at the end of each year all fish in cohorts age one and higher are moved to the next age class, and the fish movement, growth and mortality loop for the year begins anew. Although an age-one fish suddenly becomes an age-two fish at the end of the year, its weight is only incremented slightly since individual weights of fish in each cohort are increased over the year according to the fitted weight-at-age function.

Spatial heterogeneity of fish and fishing effort

Information on spatial dynamics of the fish stocks is insufficient to accurately parameterize the model and would vary with geographic location and shape of the closures.

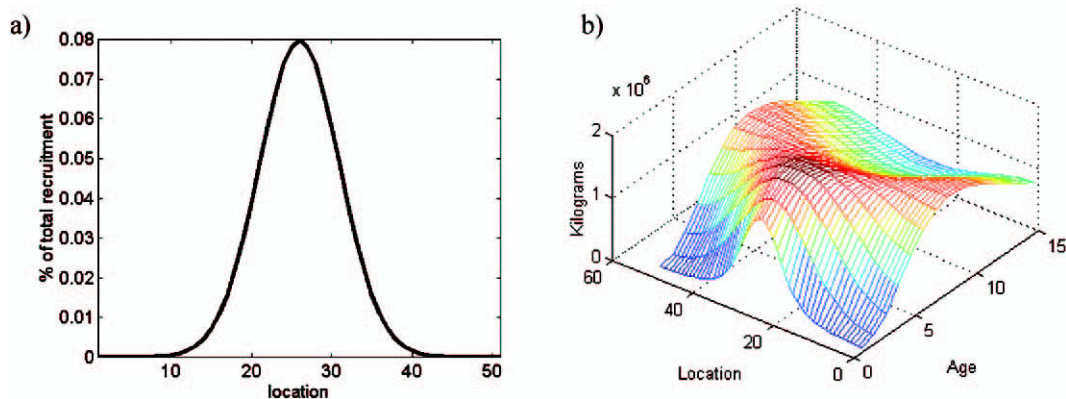


Figure 2. (a) Initial distribution of cod recruits and (b) distribution of cod by age class and location for unfished fishery in equilibrium from base single species cod model. Height on the Z-axis represents biomass for that cohort in that grid cell. Carrying capacity for fish age one and above is spatially homogenous while, for age one it has K which is proportional to the distribution of recruits shown in (a).

Consequently, we explore alternative assumptions about the spatial concentration of recruits, local carrying capacity across space and cohorts and diffusion rates. In the base model, recruits are initially concentrated in the center of the grid according to a truncated normal distribution with a standard deviation of one. The local carrying capacity, K_x , and biotic affinity, ba_x , for juveniles follow the same pattern as recruits (i.e. normally distributed with a peak in the center of the grid), but the carrying capacity and biotic affinity are assumed to be homogenous across space for adults. These assumptions lead to a spatial distribution of fish where younger fish are concentrated toward the center of the grid while the oldest age classes are more concentrated toward the edges. With no fishing, this results in an equilibrium spatial distribution shown in Figure 2b. This is not asserted to mimic the true spatial distribution of the stock. Rather it is a stylized distribution designed to explore how spatial heterogeneity in effort (through a closure or other means) might capitalize on heterogeneous distribution of age classes to improve the age composition of catch.

The spatial concentration of fishing effort is also an important determinant of fishery productivity. Again information is lacking on the degree to which effort concentrates on denser aggregations of fish. In the base model it is assumed that total effort, a control variable in the model, is distributed proportionate to potential revenue per unit effort across space with a concentration factor, CF , of 1.

$$E_{x,t} = TE \times \frac{(X \times vpue_{x,t} / \sum_{x=1}^X vpue_{x,t})^{CF}}{\sum_{x=1}^X (X \times vpue_{x,t} / \sum_{x=1}^X vpue_{x,t})^{CF}} \quad (10)$$

where TE is the total nominal effort, $vpue_{x,t}$ the potential value per unit effort in area x and X is the total number of grid cells. $vpue_{x,t}$ is approximated⁷ by:

⁷Actual value per unit effort is a nonlinear function of numbers, fishing and natural mortality, fish weights and prices; however, it differs only slightly from this approximation when the time step is small (i.e. 5 days).

$$vpue_{x,t} = \sum_{i=1}^{15} q \times p_{i,t} \times N_{x,i,t} \times w_{x,i,t} \times P_{i,t} \quad (11)$$

Multispecies model

The base cod model described earlier is extended by integrating it with identically structured models of Georges Bank haddock and yellowtail flounder. The biological models for the three species are independent in the sense that biological interactions are not modeled. However, technical interactions occur because the distribution of effort is determined by revenues derived from the three species combined. Thus $vpue_{x,t}$ from Equation (10) is summed over species, j , as well as cohorts, i .

$$vpue_{x,t} = \sum_{j=1}^3 \sum_{i=1}^{15} q_j \times p_{j,i,t} \times N_{x,j,i,t} \times w_{x,j,i,t} \times P_{j,i,t} \quad (12)$$

Various assumptions regarding the relative spatial distributions and catchability of these species are explored. Extending the advection–diffusion scheme to multiple species presents similar questions encountered with multiple cohorts. Consistent with findings in the literature (e.g. Murawski and Finn, 1988), the base multispecies model assumes that the species behave independently. Thus $LS_{x,t}$ of each species is determined only by the density of each species relative to a species specific carrying capacity and biotic affinity. They are unaffected by the distribution of other species. Carrying capacity and recruitment are assumed to vary across space differently for the three species such that each tends to concentrate in separate areas with substantial overlap. A heterogeneous but overlapping distribution is consistent with data from the bottom trawl survey conducted each spring and fall by the National Marine Fisheries Service (Figure 3). Data from a study fleet of commercial trawlers fishing Georges Bank (Holland, 2002) also indicate this type of distribution with both absolute and relative catch rates of cod, haddock and yellowtail flounder varying by depth and

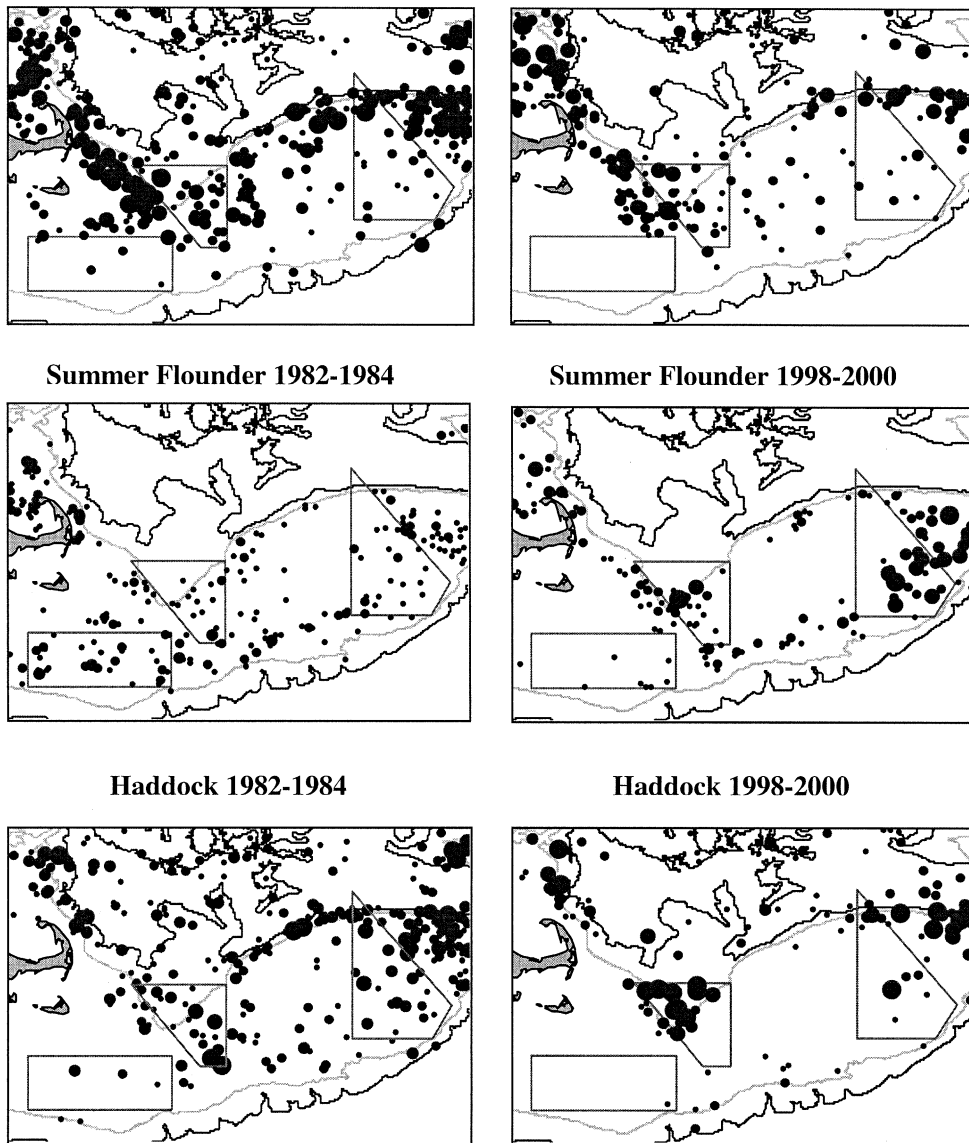


Figure 3. Catch per tow for summer flounder and cod during from NMFS bottom trawl surveys. Each figure shows all tows with positive catch during spring and fall surveys over 3 year intervals. The smallest dots represent tows with CPUE of 1–5 kg per 30 min tow. Largest dots represent tows over 75 kg tow⁻¹. Intermediate size dots represent 5–15, 15–35 and 35–75 kg tow⁻¹, respectively.

location (Figure 4). Figure 5 shows the equilibrium distributions of the cod, haddock and yellowtail flounder stocks for the base model with no fishing. Figure 5d shows the spatial carrying capacity, K_x , of the three species which determines the distribution of the fish stocks. As with the single species model, this is not meant to accurately represent the actual spatial distribution or degree of overlap between these species but is a stylized spatial assumption which enables us to explore the utility of closures for altering

relative species catch rates when species distribution is spatially heterogeneous. Note that the assumptions made about cod distribution are different from those in the single species cod model. Adults as well as juveniles are modeled with spatial preference in the multispecies model while in the single species cod model, only juveniles were assumed to exhibit spatial preference. The case of homogenous spatial distribution of all species is also considered along with variations in key model parameters.

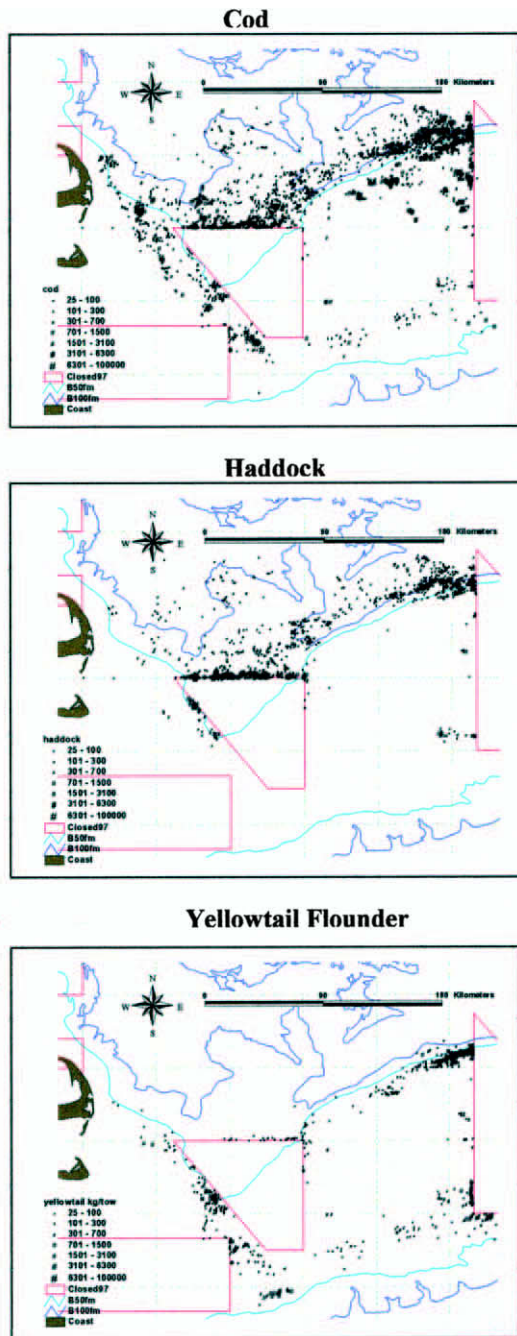


Figure 4. Spatial distribution of catch per tow by species for primary groundfish species. Data reflect total species catch from individual tows recorded by a study fleet of trawlers based in New Bedford, MA. Tows generally range from 1 to 3 h.

Management scenarios

The primary purpose of this modeling exercise is to explore the impacts of different combinations of management measures on fishery productivity and profitability. Each

simulation is run with a range of effort levels from well below to well above levels that produce maximum revenues. Effort is incremented in 2.5% increments of the highest level. These are estimated to equate with increments in nominal effort of 7.3 standard vessel years.⁸ At each effort level several mesh sizes ranging from 152 mm square mesh to as large as 203 mm square mesh are modeled. Simulations also model the result of area closures of varying sizes for each combination of effort and mesh size. For single species cod simulations, area closures are imposed in the center of the grid such that they provide maximum protection to juvenile cod. For multispecies simulations, closures are centered on the mode of the cod distribution, since overall fishery revenue is generally increased by shifting effort from areas where cod is concentrated to areas where haddock and yellowtail are concentrated. As an alternative to area closures, a series of multispecies simulations are run imposing a tax on cod revenues ranging from 20 to 80%. This has the effect of reducing the relative potential value per unit effort (from the fishers viewpoint) in areas where cod forms a high proportion of the potential catch causing effort to shift toward areas with higher haddock or yellowtail flounder concentrations. It should be noted that these simulations are deterministic and assume that nominal effort is perfectly controlled.

Results

Single species model

Figure 6a and b shows equilibrium revenue curves from the base cod model for a range of effort levels, mesh sizes and area closures. As one would expect, at low effort levels smaller mesh sizes provide higher revenues, but the reverse is true at moderate to high effort levels.⁹ Maximum revenues are achieved with the largest mesh size modeled (203 cm) and high levels of effort; however, this is unlikely to be an economically optimal policy when harvesting costs are considered since increased revenues are more than offset by the increased costs of fishing effort.¹⁰ If this were truly a single species fishery and all revenues and harvest costs were attributable to harvesting cod, the model

⁸A “standard vessel” is modeled as a 23 m, 120 gross t, 600 hp otter trawler based in New Bedford.

⁹The results with larger mesh sizes must be viewed with caution. Experiments ran only up to approximately 152 mm square mesh and the selectivity beyond that point is extrapolated based on the estimated selectivity function and is likely to be increasingly inaccurate as mesh size is increased.

¹⁰Costs are estimated using the cost simulator OTTER 2.0 (Lallemand and Gates, 1998). Costs for a standard vessel year assume 200 days of operation. Labor costs are opportunity costs of labor rather than crew share. They are based on average earnings of blue collar workers in New England from Bureau of Labor Statistics.

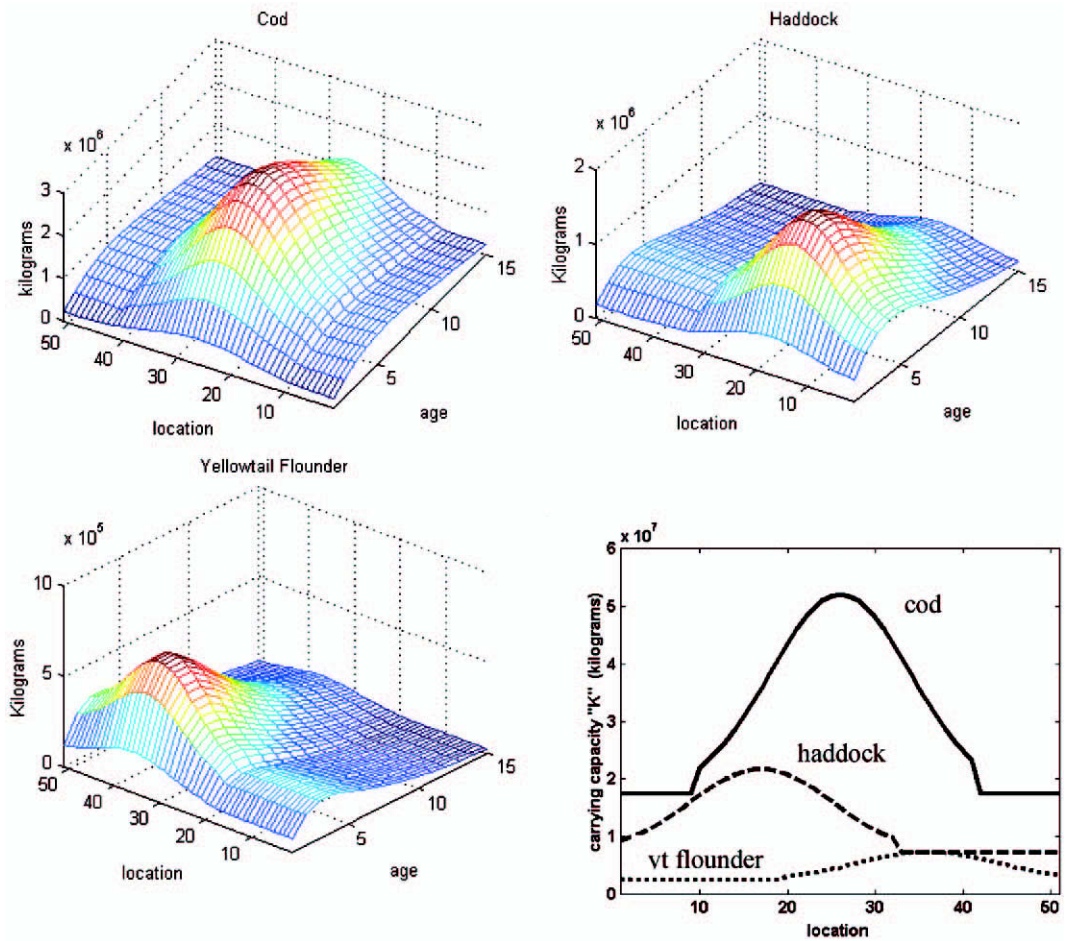


Figure 5. Distribution of (a) cod, (b) haddock and (c) yellowtail flounder biomass by age class and location for unfished fishery from base multispecies model; and (d) spatial distribution of carrying capacity, K , for each stock.

suggests that a policy of 203 mm mesh with an effort level of around 87 standard vessel years would yield maximum net revenues. This corresponds with a biomass weighted F around 0.16. Gross revenues are maximized at nearly twice that level of effort and a biomass weighted F around 0.25. With 165 mm mesh maximum gross and net revenues are somewhat lower and the effort level that generates maximum net revenues is also lower at 58 vessel years. As is discussed in the following section, consideration of other species caught in combination with cod alters the “optimal” policy significantly.

Figure 6b shows equilibrium revenue curves for 165 mm square mesh (the current minimum codend mesh size for groundfish otter trawlers on the US side of Georges Bank) and various closures sizes centered in the grid. By placing area closures in the center of the grid they provide maximum protection to juvenile fish. By reducing juvenile bycatch and increasing the average age of fish caught, area closures of 10–30% of fishable area result in small

increases in maximum potential revenue; however, they also increase the overall level of nominal effort required to maximize revenues. The highest level of net revenues is achieved with a mesh size of 203 mm and a small closure of 10% of fishable area. Even the largest area closures modeled (50% closure) result in little appreciable change in maximum gross revenues and reduce maximum net revenues by only 5%.

Area closures along the edges of the grid were also modeled. These would tend to provide protection to older age classes and might be expected to increase recruitment as a result. However, by diverting effort toward the center of the grid they tend to increase mortality of younger age classes and increase growth overfishing. With a mesh size of 165 mm, any area closure along the edges decreases the maximum net revenues achievable (Figure 7a). Unlike closures centered in areas where juveniles are concentrated, large closures fail to maintain revenues at high effort levels. The large edge closures still maintain higher levels of SSB

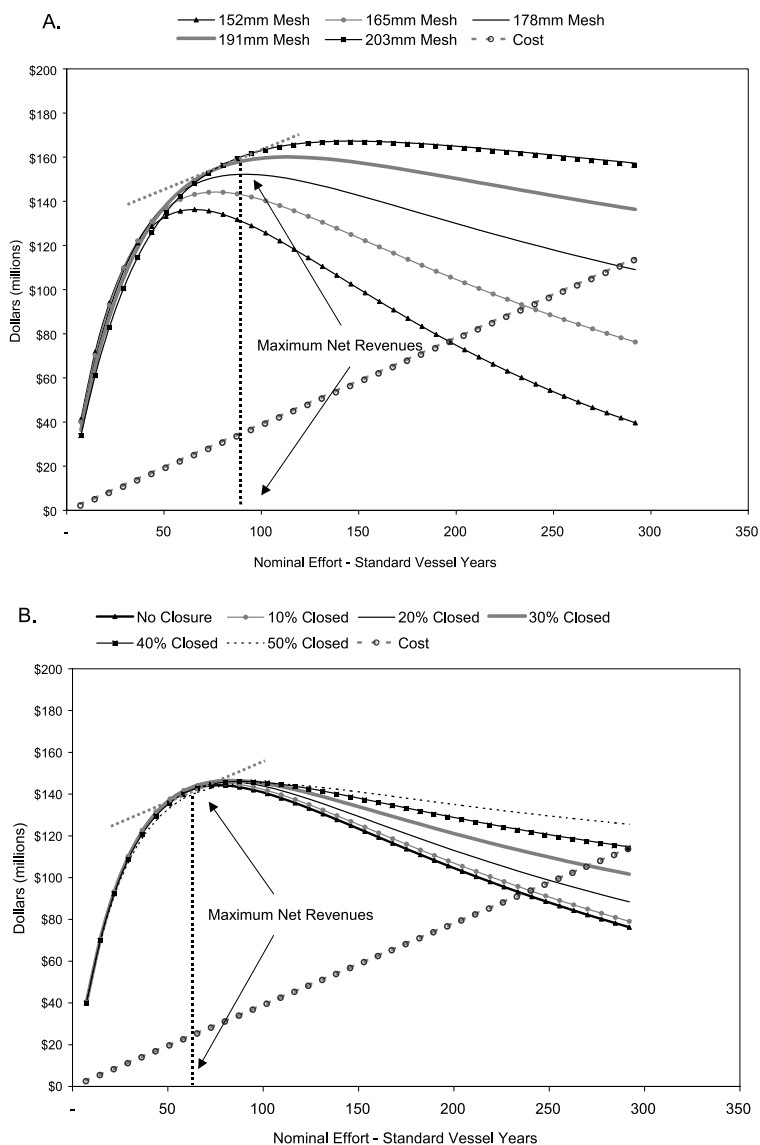


Figure 6. Revenue curves for (A) alternative mesh sizes with no closures and (B) alternative closure sizes with 165 mm square mesh (the current legal minimum) from simulations with the base single species cod model. The tangency of the total cost curve with the outer envelope of the revenue curves determines the point of maximum net revenues.

at high effort levels, but effort becomes strongly concentrated on juveniles and smaller fish leading to growth overfishing. With a larger mesh size of 203 mm, small edge area closures of 10 or 20% have almost no effect on maximum gross or net revenues (Figure 7b). The combination of large mesh and edge closures tends to control growth overfishing (mesh size) and slightly increase SSB and recruitment.

Along with catch and revenues, SSB is a common management reference point. SSB may be considered as an indicator both of potential productivity of the fish stock and of the risk of depletion or collapse. For the single species

cod model, the equilibrium SSB levels corresponding with effort levels that generate maximum net revenues increase with the size of the area closures. Table 2 shows the SSB, net revenues and effort levels corresponding with maximum net revenue assuming a mesh size of 165 mm and a range of closure sizes. Although net revenues decline by about 3% from the maximum level as the closure is increased to 50%, SSB rises by around 16%. It should also be noted that, at high effort levels, area closures maintain both higher levels of revenues and higher SSB than no closures.

These results are reasonably robust to changes in assumptions about the diffusion rate and the concentration

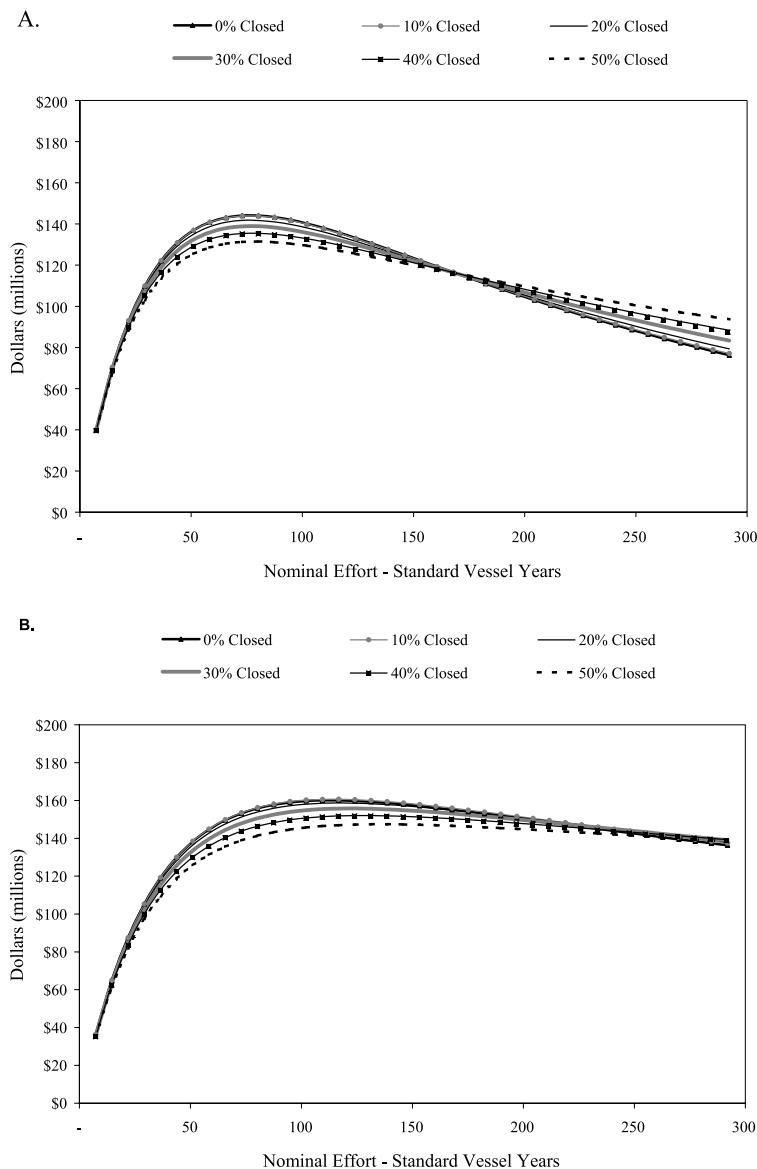


Figure 7. Revenue curves for various closure sizes along the edge of the grid for (A) 165 mm square mesh (the current legal minimum) and (B) 203 mm mesh. These are simulations with the base single species cod model, however, symmetric closures are implemented along the edges of the grid where they tend to provide relatively more protection to older age classes. The revenue curves for 0 and 10% closures for both 165 and 203 mm meshes are virtually indistinguishable and produce higher maximum revenues than larger closures.

of fishing effort. Within the range of optimal management measures (i.e. moderate effort and area closures of 20% or less) results are very robust. With mesh size fixed at 165 mm and assuming a 20% area closure, doubling the diffusion rate had little appreciable impact on revenue curves relative to the base model except at very low effort levels (less than 40 vessel years) where revenues tend to rise more quickly (Figure 8a). The difference is more pronounced with 40% closures (Figure 8b), but still quite small

at moderate effort levels. Increasing the effort concentration factor tends to reduce revenue slightly relative to the base model at high effort levels but has little impact at moderate effort levels for either 20 or 40% closures.

In the case of a spatially homogeneous population, area closures reduce revenues relative to the base model (Figure 8a and b). The reductions are small with a 20% closure but more significant with a 40% closure. In models with spatially homogeneous population area closures of any size

Table 2. Spawning-stock biomass at effort levels corresponding with maximum net revenues with a mesh size of 165 mm for the single species cod model.

	Net revenue (US \$ millions)	Effort (vessel years)	SSB (1000's tonnes)
No Closure	118	58.4	370
10% Closed	119	58.4	373
20% Closed	119	58.4	381
30% Closed	119	58.4	391
40% Closed	117	65.7	405
50% Closed	115	65.7	423

reduce maximum net revenues relative to no closure, but losses in revenues are still not large even for large closures. For example, a closure of 50% with 165 mm mesh reduces maximum equilibrium revenues by only about 7% and closures of 10–30% result in little appreciable change in maximum revenues. Area closures continue to conserve both SSB and stock productivity at high effort levels under the assumption of homogeneous spatial preferences across age classes.

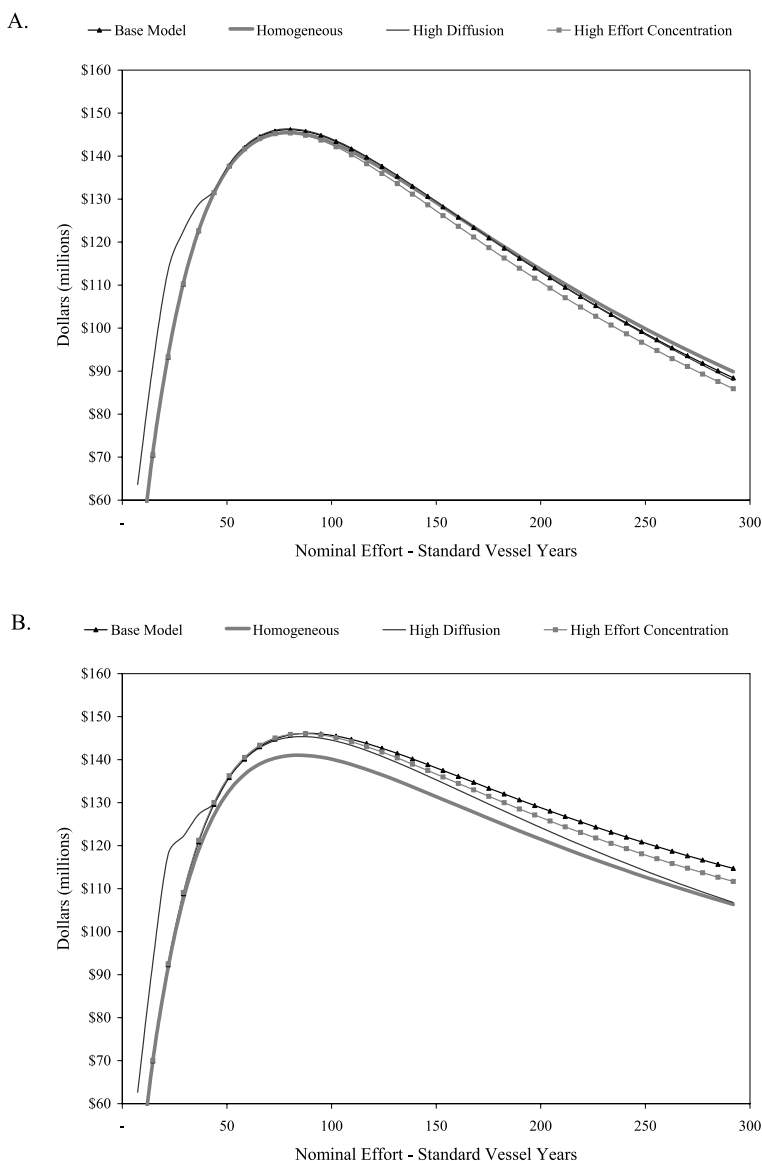


Figure 8. Revenue curves from sensitivity analysis with single species cod model. Mesh size is fixed at 165 mm and revenue curves, with area closures of (A) 20% and (B) 40%, are shown for the base model, homogeneous distribution of recruits and carrying capacity, doubled diffusion rate and a doubled effort concentration factor.

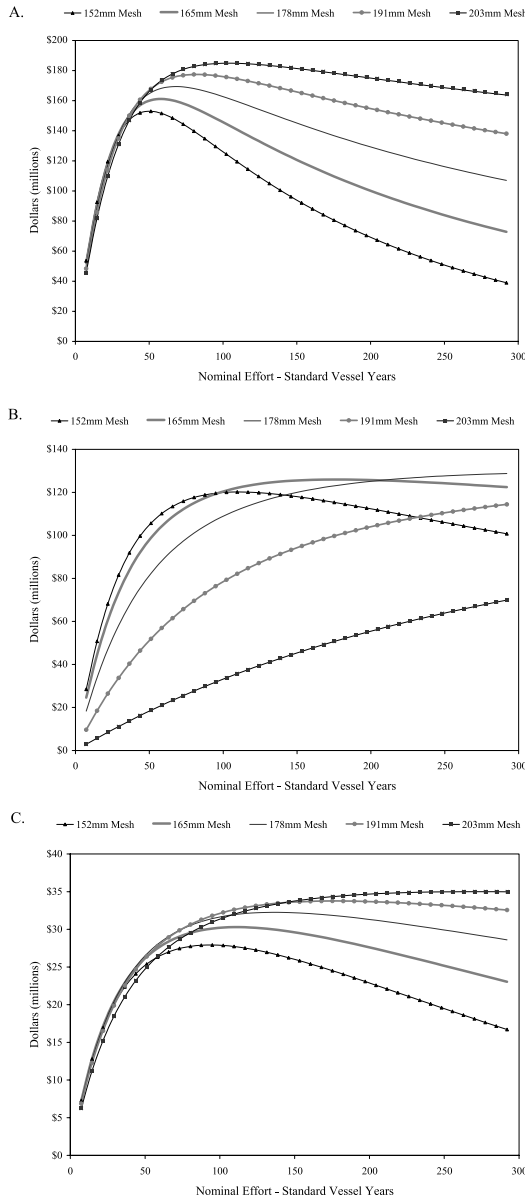


Figure 9. Revenue curves for (A) cod (B) haddock and (C) yellowtail flounder with alternative mesh sizes from simulations with base multispecies model.

Multispecies model

Figure 9 shows equilibrium revenue curves for cod, haddock and yellowtail flounder for a range of mesh sizes. While cod revenue curves (Figure 9a) increase with mesh size and peak at relatively low effort levels, haddock revenues (Figure 9b) decrease dramatically with larger mesh sizes and require relatively high effort levels to achieve maximum revenues even with smaller mesh sizes. Yellowtail flounder revenues (Figure 9c) also increase with larger mesh sizes though to a lesser degree than cod.

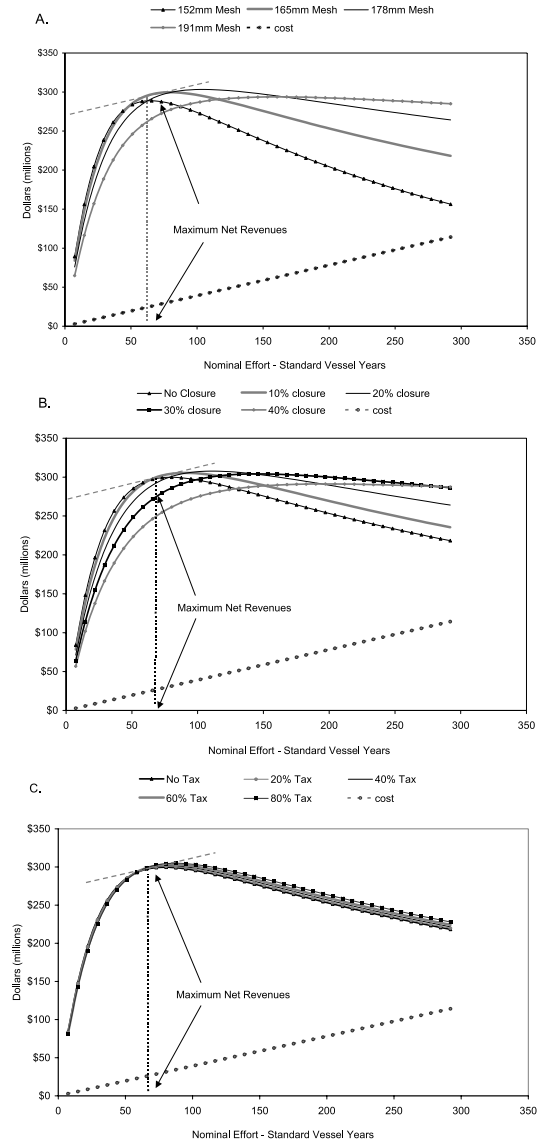


Figure 10. Combined species revenue curves for (A) alternative mesh sizes with no closures, (B) alternative closure sizes with 165 mm mesh and (C) alternative tax rates on cod revenues with 165 mm mesh from simulations with the base multispecies model. The tangency of the total cost curve with the outer envelope of the revenue curves determines the point of maximum net revenues.

Considering combined species revenues (Figure 10a), maximum revenues are achieved with the 165 mm mesh and relatively low effort levels. Maximum net revenues without closures or taxes are achieved (at the point of tangency of the cost curve and the outermost revenue curve) with 165 mm mesh and an effort level of approximately 66 standard vessel years. This management prescription results in a biomass weighted F of 0.23 for

cod but only 0.12 for haddock and 0.18 for yellowtail flounder.

Because of the spatial overlap of the three species and the lack of direct controls on the spatial distribution of effort, it is not possible to achieve high yields for all species. Effort tends to be overly concentrated on areas with highest cod densities which offer higher revenues per unit of effort. Use of area closures or taxes can provide small gains by shifting effective effort from cod to haddock and yellowtail flounder. Figure 10b shows revenue curves for different sized area closures centered on the mode of the cod biomass distribution with mesh size held constant at 165 mm. Revenue curves for various per-unit taxes on cod landings, again holding mesh size constant at 165 mm, are shown in Figure 10c. Both of these management tools provide small gains in profitability. The highest net revenues allowing for area closures are achieved with a 10% area closure combined with a 10% increase in nominal effort to 73 years. However, net revenues are increased by less than 1% from the maximum level achieved with no closure. A rather extreme tax rate of 80% with a 10% increase in nominal effort provides a similar increase in profit. It should be noted, however, that such a high tax rate would, in the absence of complete observer coverage, be likely to result in high grading or discarding of the taxed species which would defeat the purpose of the tax.

A similar effect to that achieved with a tax on cod landings results when the effort concentration factor is reduced. The effort concentration factor is not assumed to be a management variable, but examining the results of changes to this parameter is illustrative of what might be achieved with more direct control on the distribution of effort. Reducing the effort concentration factor to zero results in a homogeneous distribution of effort across space. This results in the highest level of total revenues, but not in the highest level of net revenues. The highest level of net revenues from the three species combined is achieved with an effort concentration factor of 0.5 or 0.75. Given the assumed distribution of the fish stocks, it does not appear possible to achieve a maximum yield from all three stocks without a more than proportional increase in effort and costs.

The relative gains achieved through area closures or taxes are somewhat higher if effort is more concentrated. Simulations with the effort concentration factor doubled led to essentially identical maximum net profits and the same management prescriptions (i.e. 165 mm mesh and a 10% closure) but the profits with no closures in place were slightly lower. This is to be expected since the effort distribution was even more skewed toward the cod stock. The relative change in results compared to the models using taxes to shift effort were similar. Maximum net revenues with no taxes were somewhat lower while maximum net revenues with the optimal tax (again 80%) were marginally higher than the base model.

The small gains achieved with area closures or taxes are possible because of the spatial heterogeneity of the two stocks. In the extreme case where both stocks are distributed evenly throughout the domain of the model, area closures of any size result in reductions in maximum revenue and maximum profit. For example, a 10% closure with 165 mm mesh results in a decrease in maximum net profits of approximately 1%. However, as was the case with the base model, large closures can be imposed with relatively small losses in revenues or profits. A 40% closure reduces maximum net profits by only 6%. Changing tax rates would have no impact in the spatially homogeneous case since it would not change the distribution of the fleet which, like the fish stocks, is spatially homogeneous.

In the base multispecies model, area closures centered on the mode of the cod distribution tend to decrease fishing mortality on cod while increasing it on the other two species. As one might expect, for a given level of total net revenues, this tends to increase the level of cod SSB while leading to a decrease in haddock and yellowtail flounder SSB. Table 3 shows the SSB, net revenues and effort levels corresponding with maximum net revenue from the multispecies model assuming a mesh size of 165 mm and a range of closure sizes.

Discussion

While these modeling results must be judged as preliminary and qualitative, they suggest that in a well-managed fishery, area closures are unlikely to significantly increase net revenues in equilibrium. If fish stocks are homogenous in space across age classes and species, and if managers have perfect information and precise control over effort and mesh size, these model results suggest that in equilibrium maximum yields and profitability are achieved with spatially homogenous effort. Area closures or other measures to influence the distribution of effort tend to result in decreases in net revenues.¹¹

In a single species context, spatial heterogeneity in the distribution of the fish stock and fishing effort can provide limited opportunities to increase fishery productivity when there is spatial heterogeneity across age classes and selectivity is improved by moving fishing effort away from areas with high juvenile concentrations. However, the impacts of area closures relative to those from changes in mesh sizes and effort levels tend to be quite small. These results are consistent with previous spatial modeling studies of this fishery (e.g. Polacheck, 1990; Holland, 2000). The potential benefit of area closures varies depending on assumptions about the spatial concentration of juveniles, diffusion rates and

¹¹Spatial heterogeneity in harvesting costs might still lead to suboptimal effort distributions, but this was not explored with these simulations. Area closures may also be a useful tool for rebuilding depleted fisheries.

Table 3. Spawning-stock biomass of cod, haddock and yellowtail flounder at effort levels corresponding with maximum net revenues with a mesh size of 165 mm for the multispecies model.

	No closure	10% Closed	20% Closed	30% Closed	40% Closed
Max net revenue	271	274	270	258	236
Effort at maximum net revenue	65.7	73.0	87.6	102.2	109.5
Cod SSB	269	287	309	360	422
Haddock SSB	238	228	216	209	223
Yellowtail SSB	67	60	51	45	45

Note that the effort level (in standard vessel years) that generates maximum net revenue increases substantially with the size of the closure.

concentration of effort, but, qualitatively, the results are robust to the suite of assumptions in the sensitivity analysis.

The utility of area closures is more apparent in a multispecies context if there is substantial spatial heterogeneity in the distribution of species and markedly different selectivity or productivity across species. However, potential gains from using area closures or taxes to manipulate the distribution of effort still appear to be limited. This is partly the case because redistributions of effort away from areas with the highest concentrations of cod increase the total cost of achieving a given level of combined revenues from the three stocks. Controls on effort and appropriate mesh size selection continue to be the dominant management measures. As with the single species model, optimal levels of the three management variables are interdependent.

Spatial management may also impose additional management costs. Assuring compliance with area closures can be costly if at sea enforcement is required. These costs may be considerably lower if vessel monitoring systems are required. Effective use of area closures, particularly in multispecies fisheries, also requires large amounts of information about spatial dynamics. The surveys and port sampling programs that generate data for current stock assessment are not designed to provide information on spatial heterogeneity within or across fish stocks or on spatial dynamics. Collecting this information will be costly and the possible benefits of area closures must be balanced against these increased costs.

Although, these models failed to show large benefits of area closures for well-managed fisheries where managers have both perfect information and perfect control over effort, those assumptions often do not hold in the real world. These models did not directly explore the utility of area closures when there are environmental shocks or management failures, but they provide some insight into the benefits they might provide in such a case. The models suggest that large area closures, as high as 30% of the total fishable area, can be imposed with less than a 5% loss in net revenues. In the single species cases, moderate size area closures allowed for both increase in net revenues and in SSB. With the largest area closures, net revenues declined slightly, but SSB increase significantly which might tend to provide a buffer against stock collapse in the case of environmental changes or

management failures resulting from poor information about stock status or failure to control fishing effort or catch (Lauck *et al.*, 1998). In the single species case, both harvests and SSB are maintained even at high effort levels. However, if area closures are not centered on aggregations of juveniles, these benefits are not realized.

The utility of area closures in protecting against management failures is less clear in the multispecies case. The multispecies model demonstrates that gains in SSB for some stocks resulting from closures lead to reductions for other stocks that are more aggregated in areas to which effort is displaced. Whether or not this is desirable would depend on the relative strength and resiliency of the stocks. Incorrectly sited closures might aggravate risks of depletion or collapse of some stocks.

Although it was beyond the scope of this model to investigate this possibility, habitat protection may provide value, either by increasing fishery productivity through increased growth or lower natural mortality of commercial stocks or by protecting noncommercial species. Furthermore, if closures protect spawning aggregations, they may increase the likelihood of successful spawning events. If so, area closure may be more beneficial than these simulations suggest. It should be noted, however, that achieving the same yields and profitability with area closures may require significantly more nominal effort. Thus the intensity of fishing in areas remaining open may be greatly increased. This raises the important question of whether the habitat can better sustain moderate effort spread broadly or effort that is patchy but concentrated.

All stock assessment tools require data which is typically quite costly to collect. These modeling exercises provide useful insights into the importance of different types of data. The models suggest that the benefits of area closures in improving size selectivity are limited, particularly if large mesh sizes are in use. However, information on selectivity of the larger mesh sizes modeled is imprecise at best and there is little if any data on incidental mortality of fish passing through the mesh. Better information on gear selectivity and incidental mortality is necessary to validate the benefits of particular mesh size regulations. In the single species context, it would seem that the value of area closures is dependent on as yet unsubstantiated benefits from in-

creased growth or reduced mortality (particularly at pre-recruit stages). A better understanding of how and whether area closures will provide these benefits is necessary to validate their benefits and also to aid with their design.

While area closures appeared to provide some benefits in tuning relative fishing mortalities in a multispecies fishery, it is also clear that other measures such as taxes might achieve similar results. However, taxes on landings of some species, unless they were returned to the industry as a lump sum transfer, would almost certainly encounter great resistance from industry. Individual quotas would provide similar economic incentives for fishermen to adjust species catch composition and might be more acceptable, particularly if quotas are originally gifted to the industry. The use of closures may be particularly problematic if the mix of species changes over small distances and seasonally based on depth and bottom type. In this case it may not be feasible to design or enforce effective area closures.¹² Understanding fishermen's response to management measures in terms of their species targeting behavior may be as important as understanding the spatial dynamics of the fish.

This paper demonstrates the need for comprehensive analysis of the overall management system as opposed to isolated assessments of particular management measures for individual species. The optimal management mix for a group of species is likely to differ from that which appears to maximize productivity for any one species. For example, changes in mesh size may lead to dramatic increases in yields for one species but cause greater decreases in revenues for other species. It is important to consider the effects of management decisions on costs as well as revenues since management measures that increase revenues may also increase costs. Management strategies that attempt to maximize equilibrium net revenues will normally require lower effort levels than those which maximize gross revenues in equilibrium. Optimal levels of different management measures will most often vary interdependently. For practical or political reasons, it is often not possible to optimize the entire package of management measures (i.e. it may not be feasible to reduce nominal fishing effort) in which case the optimal levels of mesh size and area closures are likely to be different from those prescribed when effort is lower.

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¹²The US Coast Guard which is responsible for at-sea enforcement of fishery regulations in US waters has consistently and successfully opposed area closures based on bathymetry because of enforcement difficulties.