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Fishing effort redistribution in response to area closures

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ABSTRACT

Spatial fishery closures will induce fishing effort to either move to open areas or to cease to fish. When designing a short- or long-term closed area management regime, the expected impact of that closure will depend upon how that effort is redistributed. We present a redistribution model based upon Ideal Free Distributions (IFDs) which is intermediate in complexity between analyses in which effort is distributed uniformly over open areas and models of full fleet dynamics. The IFD models incorporate the fundamentals of the decision process invoked by fishers facing relocation and the ensuing catch rates that result from the addition or removal of effort. Two classes of models were tested: an Availability model where catch rate declines were proportional to abundance; and an Abundance model where abundance declines at an exponential rate with the entry of displaced effort into an area. Results of these models were compared with uniform and proportional redistribution methods. The IFD-based methods included relative cost of relocation, thereby illustrating the importance of both catch rates and movement costs in designing closed area regulations. To demonstrate the methods, hypothetical area closures to United States pelagic longliners in the western Atlantic were examined and the impact of those closures on bycatch rates was evaluated. Guidance for selecting an appropriate model structure for a particular closed area problem is given.

1. Introduction

The response of fishers and their fishing effort to management actions is important when developing effective regulations. Management actions alter the economic conditions that fishers face; in response, individual fishers make decisions changing their future behavior (Sanchiro and Wilen, 2005). These responses can be especially complicated when evaluating spatial closures. Spatial analysis of effort is integral to the design of closed areas. One way to address the movement of effort is by modeling fleet distribution characteristics (Hilborn and Walters, 1987; Babcock and Pikitch, 2000; Dorn, 2001, Little et al., 2004; Smith et al., 2008), where factors leading to effort decisions have been explicitly incorporated.

Interest in spatial management of the marine environment has increased in recent years (Pauly et al., 2002). This includes short-term closures in which areas are closed for only a few months out of the year to specific fisheries (NMFS, 2006), permanent closures to specific fisheries (NMFS, 2006) and Marine Protected Areas (MPAs) where areas are permanently closed to most if not all fishing activity (Polunin, 2002; Russ and Alcala, 2004; Sanchiro and Wilen, 2001). In the case of either short- or long-term spatial closures, the impact of those closures will largely depend upon the redistribution of displaced effort. While fleet dynamics models are useful in developing understanding of fleet behavior, it is difficult to parameterize them and to translate their results into impact analyses when designing closure regimes. A simplistic alternative to fleet dynamics models may be based upon the assumption that displaced effort is distributed uniformly outside a closed area (NMFS, 2006). A potentially more realistic alternative would be to assume that displaced effort is distributed over open areas in proportion to the catch rates or effort that exists in those areas. While these approaches may be useful approximations in specific circumstances, they do not specifically address fleet behavior.

We introduce an intermediate option that uses the same data required for the simple distribution models above and is computationally simple, yet incorporates the basic decisions that fishers are faced with when being displaced from a closed area. Incorporating these basic decisions does not require a full-blown fleet dynamics model. The approach employed here is based upon Ideal Free Distributions (IFDs). While IFDs were originally proposed for the ecological distribution of animal populations (Fretwell and Lucas, 1970), applications include temperature distributions in physics (Quijano and Passino, 2007) and spatial control designs in engineering (D'Andrea and Dullerud, 2003).

The principle of an IFD is that the suitability of a spatial area to an agent (in this case a unit of effort) is altered by the number of agents that occupy that area. An agent searches for the area in which its suitability is maximized by comparing its current location to

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$$
\begin{array}{ll}
Z_{i,h}(t) = \max_j (S_j(t)/V_{i,j}) & \text{where } h \text{ is the area that maximizes } S_j(t)/V_{i,j}\ i \neq j \\
\text{If } Z_{i,h}(t) > S_i(t)/V_{i,i} > L & \text{then effort moves from area } i \text{ to area } h \\
\text{If } Z_{i,h}(t) < S_i(t)/V_{i,i} > L & \text{then effort stays in area } i \\
\text{If } Z_{i,h}(t) < L \text{ and } S_i(t)/V_{i,i} < L & \text{then effort is removed from area } i \text{ to 0 (ties-up)}
\end{array}
\quad (1)
$$

alternative areas; if the suitability per moving cost of an alternative area is higher than the agent's current location, and then the agent moves. When all of the agents have no areas that provide better suitability per movement cost, then no net movement occurs and an equilibrium solution has been reached; this equilibrium condition is referred to as an IFD. Quijano and Passino showed that this IFD is a Nash equilibrium (Gintis, 2000) and an evolutionary stable strategy (Taylor and Jonker, 1978; Maynard-Smith, 1982).

In this study, we explore modeling options in which suitability is defined as the expected catch per effort in an area per the cost of moving to that area. Analytical solutions for the suitability models we suggest could not be easily achieved. Therefore, a solution was found using a simple simulation computational method. This paper formally presents the suitability models and then illustrates the method with an application to proposed closures within the western Atlantic to US pelagic longliners (NMFS, 2006). In the illustration, we explore alternative model structures and the consequences of using each. Finally, a discussion of the assumptions and guidance for choosing a modeling option are presented.

2. Effort redistribution models

Let there be $M+1$ areas into which effort can be displaced. The effort in those areas is labeled E_i (i = 0,1,2, . . ., M). Area 0 denotes the effort that stops fishing in response to a closure, i.e. the fishers that choose to not move to other areas and cease fishing. We will refer to this area 0 as "tie-up," as the vessels tie up at the dock. Assume all areas $i \neq 0$ have effort in them prior to a closure. When an area is closed then the effort that occurred there prior to closure is displaced. Let $D_{i,j,k}(t-1)$ denote effort that occurs in open area i at time step $t-1$, moves to open area j during the period $t-1$ to t and that effort originated (at $t=0$) in area k. Additionally, $\Sigma_j D_{m,j,m}(0) \equiv E_m$, i.e. the displaced effort at the time a closure is initiated ($t=0$) is equal to the observed effort in a closed area m.

The observed catch by area is C_i and the observed catch-per-unit-effort (CPUE) is C_i/E_i. Note that the catch model may be generalized so that it is composed of the weighted sum over species, i.e. $C_i = \Sigma_g \omega_{i,g} c_{i,g}$, where $c_{i,j}$ is the catch of species g in area i and $\omega_{i,j}$ are the weights (for example, ex vessel prices derived from each species). Additionally, there is a cost of moving a unit of effort from areas i to j, V_{ij} (i = 1,2, . . ., M; j = 1,2, . . ., M), where $V_{ii} = 1$, thus the costs are expressed relative to a cost of unity for the case of no movement.

When effort is displaced due to a closure, it must either move to an open area or tie up. The rule by which that decision is made is based upon the expectation of the CPUE in the destination area and upon the cost of moving. The suitability function used in IFD models (e.g. Quijano and Passino, 2007) is defined here as the expected CPUE at a particular time step (t) in this analysis. Thus, suitability for area i is defined as $S_i(t)$. Therefore, the benefit–cost ratio of moving one unit of effort from area j to area i is $S_i(t)/V_{j,j}$. It is assumed that a unit of effort will only move to another area if the benefit–cost ratio $[S_i(t)/V_{j,i}]$ is larger in the destination area than in the originating area. Therefore, the decision rule is to choose the area with the maximum benefits–cost ratio. Additionally, there is a minimum threshold level of suitability, L, at which the decision will be made to no longer fish and effort is tied up. Let $Z_{i,h}(t)$ be the maximum suitability per movement cost by area, where i is the area in which the effort originates and h is the area in which $S_j(t)/V_{i,j}$ is maximized (over all j open areas). Thus, the decision rule faced by a unit of effort in area i is:

2.1. One-step versus multi-step effort movement cost

In calculating the cost of effort movement en route to the equilibrium solution, two approaches were considered. In the first, referred to as the One-step approach, effort movement was calculated sequentially for each displaced agent and the cost of each move was calculated based on the original area at the initiation of the process. At all subsequent steps, the suitability of moving to a new area was re-evaluated but the cost was always calculated relative to the original area. Alternatively, in the Multi-step approach, the cost of movement was updated at each step and was calculated based on the location at the previous simulation step. The first method implies that the equilibrium suitability is achieved after one decision of movement for each unit of effort, whereas the latter allows the cost of movement to be updated as effort moves through multiple steps.

2.2. Displacement versus redistribution

Two approaches were considered in addressing the movement of effort due to closures. In the Displacement model, it is assumed that the only effort that moves is that effort that is displaced by the closure. Effort that exists in the open areas will remain in those areas without movement. Alternatively, the Redistribution model assumes that both efforts displaced by a closure and effort that originally existed in the open areas redistribute to a new equilibrium. Let $X_j(t)$ be the effort that occurs in area j at time t. The displacement model assumes

$$X_j(t) = \sum_{i,m} D_{i,j,m}(t-1) + E_j - \sum_{i \neq j,m} D_{j,i,m}(t-1) \quad (2)$$

where area j cannot be a closed area ($\Sigma_{i,j,m} D_{i,j,m}(t) = \Sigma_m E_m$). Conversely, in the Redistribution model all effort that occurs in area j is a candidate for movement, not just the effort that was originally displaced by the closure ($\Sigma_{i,j,k} D_{i,j,k}(t) = \Sigma_m E_m + \Sigma_j E_j$),

$$X_j(t) = \sum_{i,k} D_{i,j,k}(t-1) - \sum_{i \neq j,k} D_{j,i,k}(t-1) \quad (3)$$

Displacement assumes that only the effort originally displaced by closure will move and a new equilibrium is achieved without movement of the non-displaced effort. Redistribution implies that all effort can be relocated to a new equilibrium.

2.3. Suitability models

Recall that the suitability function describes the expected CPUE of moving a unit of effort. When utilizing suitability models for an IFD, it is assumed that the addition or subtraction of effort in an area will change area-specific CPUE, making it more desirable when effort is moved from that area and less desirable when effort is moved to that area. We explore two classes of CPUE suitability models in which this principle is demonstrated. Additionally, each of these models is modified to accommodate the cost calculation (One-Step versus Multi-Step) and the effort being distributed (Displaced versus Redistributed).

The first suitability model is termed the Availability Model, denoting the assumption that the amount of fish available to be caught in an area is constant and the catch available is apportioned to all the effort that exists in that area. The Availability Model is defined as

$$S_i(t) = \frac{C_i}{X_i(t)} \tag{4}$$

This is similar to the class of models in Quijano and Passino (2007).

Alternatively, an Abundance Model may be used which assumes that the abundance of fish is depleted by the effort in an area, leading to

$$S_i(t) = \left[\frac{C_i}{E_i}\right] \exp[-\alpha(X_i(t) - E_i)] \tag{5}$$

where α is the rate of depletion in CPUE with the addition of one unit of effort. The implication of (5) is that the abundance in an area (as measured by CPUE) declines due to the additional effort being imposed. The special case when $\alpha = 0$, implies that CPUE is unchanged by additional effort. Therefore, effort will migrate to the area with the highest CPUE per cost, unless it is exceeded by the threshold tie-up criteria, L.

The suitability models are monotonic functions of displaced or redistributed effort. Linear transformations of suitability and powers of suitability will result in the same solution because the decision rule is based upon suitability comparisons between areas. Thus, the solution is invariant using a utility function of effort with these properties.

2.4. Solution methods

The equilibrium solution to the effort redistribution problem is found by iterating the movement decisions for each unit of effort until all units of effort remain in an area. If there were large amounts of effort and there were no movement costs, then at equilibrium CPUE would be constant across areas. However, in most applications, equality of CPUEs is not achieved due to costs of moving. Simulation solutions were obtained by first creating a list of each unit of effort and then tracking each unit's original source area at $t = 0$, the area in which it exists at step t and the area in which it existed during the previous step, $t - 1$. Let $x_{i,j}(t)$ denote the effort in area j at time t that came from area i ($\Sigma_i\, x_{i,j}(t) = X_j(t)$). The algorithm proceeds as follows:

(1) Simulate movement from simulation step $t = 0$ to $t = T$, where T is the maximum number of iterations;
(2) Systematically select one unit of effort from the list, noting its origin (o), present location (i) and previous location (a)
(3) If the One-step approach is used then $j = o$; if Multi-step, then $j = a$;
(4) Compute $S(t)$s from Eq. (4) or (5);
(5) Find $Z_{j,h}(t)$ and h from Eq (1);
(6) Update the list for this unit of effort: present location is assigned to h; previous location is assigned to i. Then $x_{i,h}(t) = x_{i,h}(t - 1) + 1$; $x_{j,i}(t) = x_{j,i}(t - 1) - 1$;
(7) If each unit of effort has been tested, then go to 8; else go to step 2 and select the next unit of effort.
(8) If the distribution is stable ($x_{i,i}(t) = x_{i,i}(t - 1) = x_i$), then stop; else go to step 1

Note that the simulation steps are not modeling real time, i.e. a simulation step is not predicting the location of effort at a particular point in time. Rather it is a mechanism to find equilibrium solutions. Also, the stopping rule (step 8) is defined as the condition where no further movement occurs. Originally, the method selected a unit of effort randomly from the list in step 2. However, systematic selection of effort produced the same equilibrium and run times were quicker. Therefore, the systematic method was used.

2.5. Movement costs

The cost of movement to a new fishing area is dependent on many factors such as transit and fuel costs, the costs of establishing new offloading arrangements, developing new business relationships, crew costs and others. Ideally, the $V_{j,i}$ matrix should be derived from economic analyses in which these factors are determined and estimated. However, absent these detailed analyses, we suggest an approximation. First, costs are scaled such that the cost associated with no movement is equal to 1 ($V_{ii} = 1$ for all i). Then assume that the existing CPUE is a manifestation of the decision rule Eq. (1) and that the current effort distribution is in equilibrium. If such is the case, then the CPUE in area j must have been greater than or equal to the CPUE in area i divided by the movement cost; otherwise, effort would have moved from area j to i. Following this logic, it is implied that

$$\left(\frac{C_j}{E_j}\right) \ge \left(\frac{(C_i/E_i)}{V_{j,i}}\right) \quad \text{or} \quad V_{j,i} \ge \left(\frac{(C_i/E_i)}{(C_j/E_j)}\right) \tag{6}$$

As a first approximation (and as a means to explore sensitivities), we assume that if $C_iE_j/C_jE_i \ge 1$, then $V_{j,i} = \lambda\ [C_i\ E_j/C_j\ E_i]$; and if $C_iE_j/C_jE_i \le 1$, then $V_{j,i} = \lambda\gamma\ [C_i\ E_j/C_j\ E_i]$ for $\lambda \ge 1$ and $\gamma \ge 1$. This is consistent with Eq. (6) and with the assumption that $V_{j,i} \ge C_jE_i/C_iE_j$, if $C_iE_j/C_jE_i \le 1$.The parameter γ controls the asymmetry of the movement cost (costs are symmetric with $V_{j,i} = V_{i,j}$ when $\gamma = 1$) and the parameter λ controls the scale.

2.6. Bycatch impact analyses

In many instances a criteria used to evaluate the effectiveness of a closure is the change in mortality of both target and non-target (bycatch) species in the catch. While effort is displaced in relation to the CPUE of the target species (Eq. (4) or (5)), the displaced effort impacts the bycatch (non-target) species that may be retained, released alive or released dead. This impact may be estimated by comparing the estimated catch (or discards) of a non-target species (species g) after closure with the observed catch of that species prior to closure, i.e.

$$I_{species\,g} \equiv \frac{\sum_{i\,areas} c_{i,g} X_i/E_i}{\sum_{i\,areas} c_{i,g}} \tag{7}$$

Essentially impact is measured by the ratio of the predicted catch with closure relative to the observed catch prior to closure.

In the example given below, impact analyses were conducted: (1) using equilibrium solutions for X_i from alternative versions of the Availability and Abundance models with Eq. (7); (2) using values of X_i assuming that redistributions to new areas were in proportion to observed CPUE; (3) assuming that redistributions to new areas were in proportion to observed effort; and (4) assuming that all effort displaced by a closure ties up and ceases to fish.

3. Example data

The example presented is based upon the fishery management plan for the United States pelagic longline fishery (NMFS, 2006; hereafter referred to as the FMP). One objective of the FMP was to evaluate the effectiveness of closures in regards to reducing discarded bycatch of important non-target species including blue and white marlin, protected species (e.g. sea turtles) and the catch of a highly regulated species, bluefin tuna. To do this the FMP used a redistribution model in which displaced effort was distributed to open areas in proportion to the observed aggregate CPUE in open areas. In a second rendition, the FMP distributed displaced effort to the area in the closest proximity to the closure. The methods we developed are alternatives to the FMP approach.

The data used were from the Pelagic Observer Program (2001–2003). The observer datasets represent a subset of the trips analyzed in the FMP, where observers record catch and effort for each vessel-trip. While these data are appropriate for demonstrating the methods introduced here they are not the same datasets that were used in the FMP analysis, thus, the analysis should not be considered a formal comparison to the FMP. Pelagic longline catch data are recorded in numbers of animals by species. Effort is recorded as the number of hooks. The redistribution models were run with units of effort of one hook, i.e. each hook could move independently of all others. In reality the smallest unit of effort that could move would be the number of hooks associated with a vessel-trip. However, for convenience, we chose to model redistribution of single hooks. Preliminary analyses indicated this assumption did not appreciably affect the results.

Data were spatially classified into 9 areas (Fig. 1). It was assumed that effort would not be allowed to displace to the Northeast Distant area (NED) due to the highly regulated nature of that area and that effort would not be redirected to the southern areas south of the North Central Atlantic (NCA, Fig. 1). In this example we focus on a hypothetical closure of the Gulf of Mexico (GOM) to US longliners in the months of March–May. This time period and region were chosen because the GOM is the only known area of spawning of the western Atlantic bluefin tuna breeding population and March–May is the principal spawning time. In the FMP closures of smaller areas that were within the GOM were evaluated. However, because of sample size limitations of the observer data, we used a single large closed area (the GOM) to demonstrate the methods. Thus, the modeled closure of the entire GOM resulted in effort being redistributed to the open areas of: Caribbean (CAR), Florida East Coast (FEC), the South Atlantic Bight (SAB), the Mid Atlantic Bight (MAB), Northeast Coastal (NEC), Sargasso (SAR) and the North Central Atlantic (NCA). Models were run for each month (March–May) for effort displaced or redistributed from the Gulf of Mexico, thereby implicitly assuming effort cannot be transferred between months.

Catch used in the CPUE was defined as the number of yellowfin tuna and swordfish, weighted equally (the primary target species of US longliners). Also, the "tie-up" threshold CPUE (L) was specified to be 0.00235 yellowfin and swordfish per hook, the smallest observed month-area CPUE over all months and areas in which effort existed.

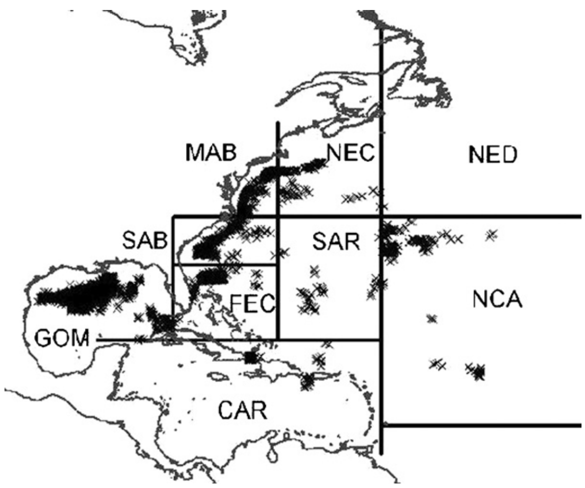

Fig. 1. Locations of longline hauls 2001–2003 from US longline observers. Area definitions are: Caribbean (CAR), Gulf of Mexico (GOM), Florida East Coast (FEC), South Atlantic Bight (SAB), Mid Atlantic Bight (MAB), Northeast Coastal (NEC), Northeast Distant (NED), Sargasso (SAR) and North Central Atlantic (NCA).

Finally, when using the abundance suitability model, an estimate of the depletion rate α is required. Ideally, a stock assessment of the target species could be used to estimate this parameter (adjusted for local abundance). In this example we simply tested alternative values of α ranging from zero to 10^{-3}. Observed catch, effort and computed movement costs by month and area are given in Tables 1 and 2.

4. Results

While predicted shifts in effort were distributed over all open areas in which CPUE was positive (Fig. 2), in March there was a tendency to move displaced effort to the Florida east coast (FEC) where the CPUE was high (Table 1) and movement costs were relatively low (Table 2). In April, movement was similar in magnitude between the South Atlantic and Mid Atlantic Bights. In May, the movement was distributed more equally over all areas.

The Displacement approach (where only displaced effort is moved to open areas) and the Redistribution approach (where both displaced effort and existing effort in open areas can redistribute) often produced the same outcomes (e.g. Fig. 2, Availability model). If an equilibrium solution results in effort by area greater than or equal to the observed effort by area (for all areas), then the outcomes will be the same between Displacement and Redistribution models. In these examples that usually was the case. Therefore, subsequent analyses focused on the Displacement approach. However, alternative cost matrices would accentuate differences between these two approaches. Additionally, differences between the One-step and Multi-step models were not consistent. In some months and areas the One-step model produced higher effort in an area than the Multi-step, while in other months the opposite was true (Fig. 2). Once movement occurred the options for changing areas were limited because the cost modulated further movement options.

With the Abundance model, as depletion rate α gets larger (Figs. 3 and 4) the impact of effort movement to an area increases, i.e. the abundance of fish and the CPUE declines due to the additional fishing mortality. Thus, with a large α (such as $\alpha = 10^{-3}$ in Figs. 3 and 4) additional effort reduces CPUE significantly, such that

Table 1
Effort (number of hooks), catch (number of yellowfin and swordfish) and CPUE (catch per 1000 hooks) from 2001 to 2003 US pelagic longline observer data during the months of March–May and for all months combined (January–December).

	March			April		
	Effort	Catch	CPUE	Effort	Catch	CPUE
CAR	0	0	0	0	0	0
GOM	47050	368	7.821	18046	181	10.030
FEC	52409	469	8.949	7315	71	9.706
SAB	4670	42	8.994	12839	112	8.723
MAB	7996	76	9.505	0	0	0
NEC	0	0	0	0	0	0
NED	0	0	0	0	0	0
SAR	8795	57	6.481	0	0	0
NCA	13446	233	17.329	0	0	0
Total	134366	1245	9.266	38200	364	–

	May			All months		
	Effort	Catch	CPUE	Effort	Catch	CPUE
CAR	2376	44	18.519	27938	554	19.830
GOM	75445	719	9.530	482407	4290	8.893
FEC	7942	63	7.933	100668	973	9.665
SAB	34117	809	23.713	90421	1410	15.594
MAB	10674	318	29.792	162200	2265	13.964
NEC	3837	29	7.558	50262	343	6.824
NED	867	8	9.227	867	8	9.227
SAR	792	4	5.051	15547	142	9.134
NCA	38145	354	9.280	60443	780	12.905
Total	174195	2348	13.479	990753	10765	–

Table 2
Relative movement costs ($V_{i,j}$) computed with scale, λ, equal to 1 and symmetric movement costs ($\gamma = 1$) for months March–May.

March

From *i*/To *j*	CAR	GOM	FEC	SAB	MAB	NEC	NED	SAR	NCA
CAR	–	–	–	–	–	–	–	–	–
GOM	–	1.00	1.14	1.15	1.22	–	–	1.21	2.22
FEC	–	1.14	1.00	1.00	1.06	–	–	1.38	1.94
SAB	–	1.15	1.00	1.00	1.06	–	–	1.39	1.93
MAB	–	1.22	1.06	1.06	1.00	–	–	1.47	1.82
NEC	–	–	–	–	–	–	–	–	–
NED	–	–	–	–	–	–	–	–	–
SAR	–	1.21	1.38	1.39	1.47	–	–	1.00	2.67
NCA	–	2.22	1.94	1.93	1.82	–	–	2.67	1.00

April

From/To	CAR	GOM	FEC	SAB	MAB	NEC	NED	SAR	NCA
CAR	–	–	–	–	–	–	–	–	–
GOM	–	1.00	1.03	1.15	–	–	–	–	–
FEC	–	1.03	1.00	1.11	–	–	–	–	–
SAB	–	1.15	1.11	1.00	–	–	–	–	–
MAB	–	–	–	–	–	–	–	–	–
NEC	–	–	–	–	–	–	–	–	–
NED	–	–	–	–	–	–	–	–	–
SAR	–	–	–	–	–	–	–	–	–
NCA	–	–	–	–	–	–	–	–	–

May

From/To	CAR	GOM	FEC	SAB	MAB	NEC	NED	SAR	NCA
CAR	1.00	1.94	2.33	1.28	1.61	2.45	–	3.67	2.00
GOM	1.94	1.00	1.20	2.49	3.13	1.26	–	1.89	1.03
FEC	2.33	1.20	1.00	2.99	3.76	1.05	–	1.57	1.17
SAB	1.28	2.49	2.99	1.00	1.26	3.14	–	4.70	2.56
MAB	1.61	3.13	3.76	1.26	1.00	3.94	–	5.90	3.21
NEC	2.45	1.26	1.05	3.14	3.94	1.00	–	1.50	1.23
NED	–	–	–	–	–	–	–	–	–
SAR	3.67	1.89	1.57	4.70	5.90	1.50	–	1.00	1.84
NCA	2.00	1.03	1.17	2.56	3.21	1.23	–	1.84	1.00

The dashes (–) denote where movement is not allowed in the analysis due to (1) there was no effort in that area, or (2) that by regulatory design no transfer of effort was allowed to that area (e.g. the analyses did not allow movement to the NED).

some effort does not move and instead stops fishing. Conversely, in the extreme case where $\alpha = 0$, there is no impact of effort movement on CPUE and the area in which CPUE per movement cost is highest is the most attractive.

CPUE of swordfish and yellowfin tuna within an area decreases when displaced effort is moved into that area (Table 3). With the Abundance model, the CPUE decrease is larger with higher values of the depletion rate, α, because the population levels are more impacted. When the depletion rate α is zero, the CPUE in the open areas remains unchanged and is the same as the observed CPUE. The threshold for ceasing fishing, L, was set equal to the lowest observed CPUE in any month of the year. This threshold was not very restrictive and no effort ceased fishing when using the Availability model (Fig. 2). Effort ceased fishing when the Abundance model was used, but only when the depletion rate α was high ($\alpha = 10^{-3}$, Figs. 3 and 4). Depletion of CPUE was large with this α value resulting in CPUEs that were below the threshold.

Analyses were repeated using alternative cost matrices in which the scale of costs was increased by 20% ($\lambda = 1.2$, $\gamma = 1$), asymmetry was increased by 20% ($\lambda = 1$, $\gamma = 1.2$) and both ($\lambda = 1.2$, $\gamma = 1.2$). In the examples used (Tables 4–6), often the effort distribution did not change much within a model, although there were exceptions (Table 5, May, $\alpha = 10{-}5$). However, these sensitivities are still based upon the same ordering of cost movements that are in Table 2.

All methods of redistribution resulting from a Gulf of Mexico closure March–May using (Table 2 cost matrix with $\lambda = 1$, $\gamma = 1$) resulted in a decrease in bluefin tuna catch and discards by US pelagic longliners of about 20% (Fig. 5). For the other species in Fig. 5, the catches plus discards increase somewhat due to redistribution of effort to areas with higher interaction rates for these species. The exception to this was where all displaced effort ceases to fish and ties up. Sea turtles killed and/or caught and released actually increased for some distribution models. The rate decreased when displaced effort tied up or moved to the area with the high benefit cost ration. Targeted catches of swordfish and yellowfin increased slightly for some models (Fig. 5). Note that a percentage change in catch by the US longline fishery would not translate directly into a change in mortality for the species concerned, since other fleets both target and/or have bycatch of these species. Thus, the proportional impact of the longline fishery on the overall mortality of these populations would be less than predicted by this analysis alone.

5. Discussion

When developing management regulations for proposed closed areas, one must evaluate the effectiveness of the proposal in achieving management objectives, often given in terms of reduced catch of one or more species. The success or failure of any closed area policy depends largely on the behavioral responses of the fishers to the closure. Their response, in turn, is dependent upon the decision rules invoked when making their redistribution decisions, generally, a personalized cost-benefit analysis. We have suggested several models for predicting behavior that incorporates observed CPUE data and relative movement costs. Our approach employs suitability models in which area-wide CPUE decreases with the addition of effort and movement of effort incurs an additional cost. These models were compared to more simplified methods in which effort was assumed to redistribute either proportionally to the existing CPUEs, proportionally to existing effort or ceasing altogether. Thus, the models we have proposed, here, are a compromise

Table 3
Catch per unit effort (number of swordfish and yellowfin per 1000 hooks) after effort was removed from the Gulf of Mexico (GOM) using the Displacement model compared to the observed (Obs) CPUE.

	Obs		Availability		Abundance							
		Step:	One	Multi	One	One	One	One	Multi	Multi	Multi	Multi
		α:			10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
March												
GOM	7.82		–	–	–	–	–	–	–	–	–	–
FEC	8.95		5.60	6.53	2.35	3.07	7.96	8.84	2.35	3.79	8.95	8.95
SAB	8.99		5.62	6.53	2.36	3.08	8.00	8.89	2.36	3.79	8.99	8.99
MAB	9.50		5.94	6.53	2.49	3.26	8.45	9.39	2.36	3.79	9.50	9.50
SAR	6.48		6.48	6.48	3.24	4.24	6.48	6.48	2.36	3.79	6.48	6.48
NCA	17.33		10.84	6.53	4.54	5.94	15.41	17.13	2.36	3.79	10.83	16.53
April												
GOM	10.03		–	–	–	–	–	–	–	–	–	–
FEC	9.71		4.49	4.79	2.35	3.54	8.10	9.53	2.35	3.73	8.41	9.53
SAB	8.72		5.00	4.79	2.61	3.94	8.72	8.72	2.48	3.73	8.41	8.72
May												
GOM	9.53		–	–	–	–	–	–	–	–	–	–
CAR	18.52		10.38	9.55	5.48	5.49	16.07	18.24	2.35	4.10	18.32	18.52
FEC	7.93		4.45	7.93	2.35	2.35	6.88	7.81	2.35	4.10	7.93	7.93
SAB	23.71		13.30	9.55	7.02	7.02	20.58	23.36	2.35	4.10	18.32	23.71
MAB	29.79		16.70	9.55	8.82	8.83	25.85	29.35	2.35	4.10	18.32	27.63
NEC	7.56		4.67	7.56	2.46	2.47	7.22	7.56	2.35	4.10	7.56	7.56
SAR	5.05		5.05	5.05	3.69	3.69	5.05	5.05	2.35	4.10	5.05	5.05
NCA	9.28		5.20	9.28	2.75	2.75	8.05	9.14	2.35	4.10	9.28	9.28

between simplistic approaches and full-scale simulation models of fleet dynamics whose parameters may not be estimable.

In constructing an analysis of the impact of a proposed closure on the distribution of fishing effort, there are questions that should be addressed when selecting an appropriate modeling approach. The overarching issue will be the availability of data to conduct the analysis. The implication is that catch and effort data prior to closure will be available at appropriate scales. Given data, then model selection should be based upon whether it is expected that the addition of effort to an area will decrease the CPUE in that area, whether the movement of a unit of effort occurs as a single decision with effort moving once or the unit of effort goes through multiple moves, and what can be estimated or inferred about the costs of movement. The final selection will depend upon the answers to these questions. However, we contend that the modeling structure that we propose organizes the decision process into appropriate

Table 4
Effort distribution using the Displaced–Abundance-Multi-step model and alternative movement cost matrices after effort was removed from the Gulf of Mexico.

	Displaced–Abundance-Multi-step				Displaced–Abundance-Multi-step			
	$\alpha = 10^{-5}$				$\alpha = 10^{-3}$			
	$\lambda = 1$ $\gamma = 1$	$\lambda = 1$ $\gamma = 1.2$	$\lambda = 1.2$ $\gamma = 1$	$\lambda = 1.2$ $\gamma = 1.2$	$\lambda = 1$ $\gamma = 1$	$\lambda = 1$ $\gamma = 1.2$	$\lambda = 1.2$ $\gamma = 1$	$\lambda = 1.2$ $\gamma = 1.2$
March								
Tie-Up	0	0	0	0	39978	39967	39961	39964
CAR	0	0	0	0	0	0	0	0
FEC	0	0	0	0	1338	1338	1338	1338
SAB	0	0	0	0	1338	1340	1341	1341
MAB	0	0	0	0	1393	1396	1397	1397
NEC	0	0	0	0	0	0	0	0
SAR	0	0	0	0	1010	1013	1015	1013
NCA	47050	47050	47050	47050	1993	1996	1998	1997
April								
Tie-Up	0	0	0	0	15368	15459	15459	15380
CAR	0	0	0	0	0	0	0	0
FEC	14360	14360	14360	14360	1419	1419	1419	1419
SAB	3686	3686	3686	3686	1259	1168	1168	1247
MAB	0	0	0	0	0	0	0	0
NEC	0	0	0	0	0	0	0	0
SAR	0	0	0	0	0	0	0	0
NCA	0	0	0	0	0	0	0	0
May								
Tie-Up	0	0	0	0	64002	64039	64015	64018
CAR	1057	1058	1057	1058	2065	2058	2063	2062
FEC	0	0	0	0	1217	1217	1217	1217
SAB	25782	25782	25782	25781	2312	2306	2310	2310
MAB	48606	48605	48606	48606	2540	2535	2538	2538
NEC	0	0	0	0	1169	1162	1167	1166
SAR	0	0	0	0	766	759	763	763
NCA	0	0	0	0	1374	1369	1372	1371

The base cost matrix was as in Table 2 using $\lambda = 1$, $\gamma = 1$. Alternative scale (λ) and asymmetry (γ) parameters were used.

Table 5
Effort distribution using the Displaced–Abundance-One-step model and alternative movement cost matrices after effort was removed from the Gulf of Mexico.

	Displaced–Abundance-One-step				Displaced–Abundance-One-step			
	$\alpha = 10^{-5}$				$\alpha = 10^{-3}$			
	$\lambda = 1$ $\gamma = 1$	$\lambda = 1$ $\gamma = 1.2$	$\lambda = 1.2$ $\gamma = 1$	$\lambda = 1.2$ $\gamma = 1.2$	$\lambda = 1$ $\gamma = 1$	$\lambda = 1$ $\gamma = 1.2$	$\lambda = 1.2$ $\gamma = 1$	$\lambda = 1.2$ $\gamma = 1.2$
March								
Tie-Up	0	0	0	0	41004	41186	41733	41915
CAR	0	0	0	0	0	0	0	0
FEC	11762	11762	25436	25436	1338	1338	1338	1338
SAB	11763	11763	7205	7205	1338	1338	1156	1156
MAB	11763	11763	7204	7204	1338	1338	1156	1156
NEC	0	0	0	0	0	0	0	0
SAR	0	0	0	0	693	511	511	329
NCA	11762	11762	7205	7205	1339	1339	1156	1156
April								
Tie-Up	0	0	0	0	15421	15603	15603	15786
CAR	0	0	0	0	0	0	0	0
FEC	18046	18046	18046	18046	1419	1419	1419	1419
SAB	0	0	0	0	1206	1024	1024	841
MAB	0	0	0	0	0	0	0	0
NEC	0	0	0	0	0	0	0	0
SAR	0	0	0	0	0	0	0	0
NCA	0	0	0	0	0	0	0	0
May								
Tie-Up	0	0	0	0	67922	68288	69018	69332
CAR	14186	15089	11148	11443	1218	1218	1035	1035
FEC	14185	15089	29379	29674	1217	1217	1217	1217
SAB	14187	15089	11148	11443	1217	1217	1035	1035
MAB	14186	15089	11148	11443	1217	1217	1035	1035
NEC	4514	0	1475	0	1121	938	938	756
SAR	0	0	0	0	315	132	132	0
NCA	14187	15089	11147	11442	1218	1218	1035	1035

The base cost matrix was as in Table 2 using $\lambda = 1$, $\gamma = 1$. Alternative scale (λ) and asymmetry (γ) parameters were used.

motivations of the fishers: benefits and costs. For example simply redistributing effort proportionally to existing CPUE or to existing effort can be translated into an Abundance model with $\alpha = 0$ with specific cost matrices. Thus, our approach organizes predictions of fisher movement decisions around the benefits (CPUE) and the costs of movement even if the final selection is a simple model.

Amongst the IDF-based models, the choice of suitability model (Abundance versus Availability) should be based upon the under-

Table 6
Effort distribution using the Displaced–Availability-Multi-step and -One-step models and alternative movement cost matrices after effort was removed from the Gulf of Mexico.

	Displaced–Availability-Multi-step				Displaced–Availability-One-step			
	$\lambda = 1$ $\gamma = 1$	$\lambda = 1$ $\gamma = 1.2$	$\lambda = 1.2$ $\gamma = 1$	$\lambda = 1.2$ $\gamma = 1.2$	$\lambda = 1$ $\gamma = 1$	$\lambda = 1$ $\gamma = 1.2$	$\lambda = 1.2$ $\gamma = 1$	$\lambda = 1.2$ $\gamma = 1.2$
March								
Tie-Up	0	0	0	0	0	0	0	0
CAR	0	0	0	0	0	0	0	0
FEC	19410	19410	19410	19410	31402	31402	36320	36320
SAB	1762	1762	1762	1762	2799	2799	1919	1919
MAB	3643	3643	3643	3643	4792	4792	3286	3286
NEC	0	0	0	0	0	0	0	0
SAR	0	0	0	0	0	0	0	0
NCA	22235	22235	22235	22235	8057	8057	5525	5525
April								
Tie-Up	0	0	0	0	0	0	0	0
CAR	0	0	0	0	0	0	0	0
FEC	7506	7505	7505	7506	8484	10196	10196	11933
SAB	10540	10541	10541	10540	9562	7850	7850	6113
MAB	0	0	0	0	0	0	0	0
NEC	0	0	0	0	0	0	0	0
SAR	0	0	0	0	0	0	0	0
NCA	0	0	0	0	0	0	0	0
May								
Tie-Up	0	0	0	0	0	0	0	0
CAR	2232	2232	2232	2232	1862	1888	1794	1818
FEC	0	0	0	0	6222	6308	8781	8880
SAB	50591	50591	50590	50591	26732	27099	25749	26105
MAB	22622	22622	22623	22622	8364	8479	8056	8168
NEC	0	0	0	0	2376	1372	2276	1287
SAR	0	0	0	0	0	0	0	0
NCA	0	0	0	0	29889	30299	28789	29187

The base cost matrix was as in Table 2 using $\lambda = 1$, $\gamma = 1$. Alternative scale (λ) and asymmetry (γ) parameters were used.

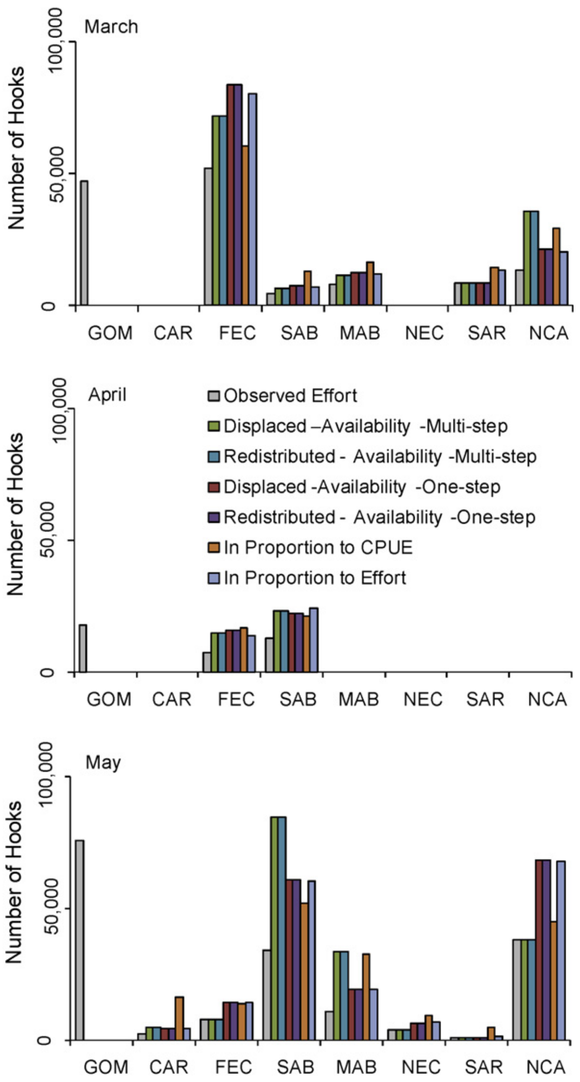

Fig. 2. The distribution of effort by area for the months of March–May observed and using alternative models and proportional redistributions. The movement cost matrix uses $\lambda = 1$, $\gamma = 1$ (as in Table 2). The observed effort in the Gulf of Mexico (GOM) is the amount of effort that is displaced by the closure and redistributed to other areas. Note also that with these scenarios no effort ceases to fish (is tied up) and that category is not given in the Figure. Methods appear left-to-right in the graph in the order that they are listed in the legend.

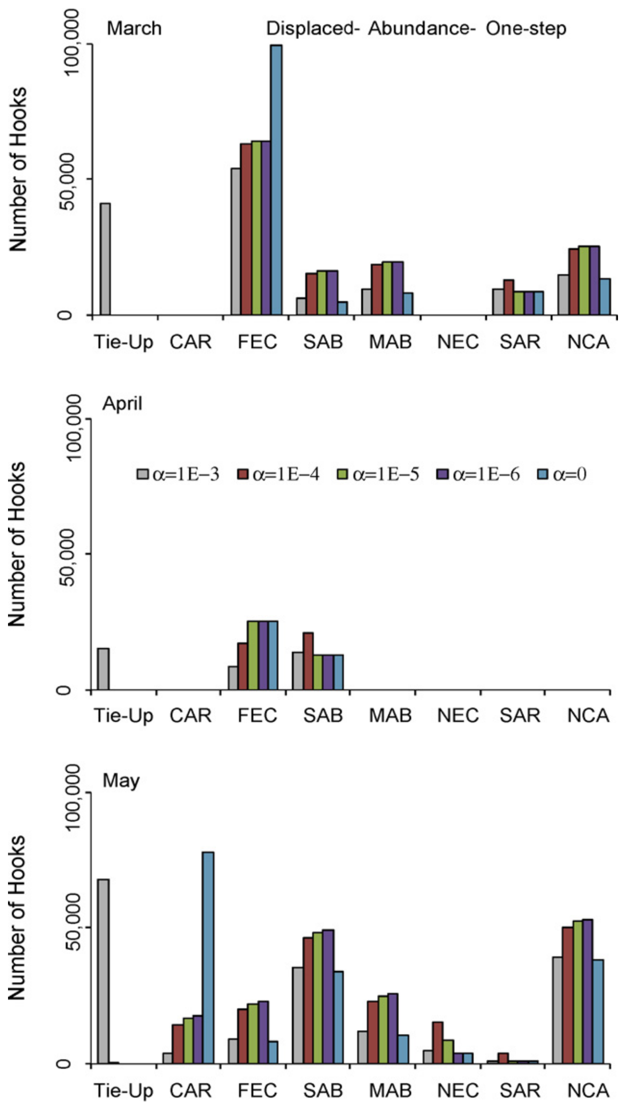

Fig. 3. The distribution of effort by area for the months of March–May using One-step Displacement with the Abundance model. The movement cost matrix uses $\lambda = 1$, $\gamma = 1$ (as in Table 2). Analyses were conducted for alternative depletion rates (α's) which appear left-to-right in the graph in the order that they are listed in the legend.

lying populations that compose the targeted catch. The Availability model purports that a fixed amount of catch is available to be divided amongst all the fishers in a given area (i.e. abundance is inversely proportional to effort). This approach may be useful in situations where area divisions are small and the availability of fish, over short time periods, is limited.

The Abundance model appears to be applicable for many situations since it is based, theoretically, upon the abundance of fish in an area. However, this implies that abundance is measured either by CPUE or through a stock assessment, and that the depletion rates α are known. If there is a stock assessment projection that includes spatial variability, then the estimated abundance of the stock(s) may be substituted for the C/E term in Eq (5). When addressing long-term impacts, it becomes more imperative that stock assessment projections be employed to account for shifts in abundance. Moreover, a formal stock assessment would provide the required estimate of α. Substitutions of the suitability functions could be used to adapt these models to particular situations, such as area-specific αs. The methodological framework developed here could easily be adapted to account for these alternatives.

After selecting the model structure (Abundance versus Availability), the choice between the One-step versus Multi-step versions will depend upon the particular conditions to be modeled. The Multi-step approach assumes that effort actually moves to open areas. Hence, options for relocating are based upon the cost of movement from the new area. This implies that the decision process occurs over an extended period (years) in which vessels move, re-evaluate their options and move again. Conversely, the One-step approach is more applicable to short-term, one-time decisions in which only one movement decision is made and at each simulation step that original decision is re-evaluated. In our example there are instances in which the Multi-step approach allocated effort to an area, whereas the One-step approach did not (Fig. 2) even though both are equilibrium solutions. In the Multi-step approach effort can move to an area early in the process. Then later in the process CPUE declines in other areas due to transfer of other effort. At that time the CPUEs in new areas have been reduced and the cost of moving to a new area is greater than one. Thus, effort gets "locked" into an area. In the One-step approach the cost of moving a unit of effort is measured relative to where that effort started. This demonstrates that selection of movement type should depend upon whether fish-

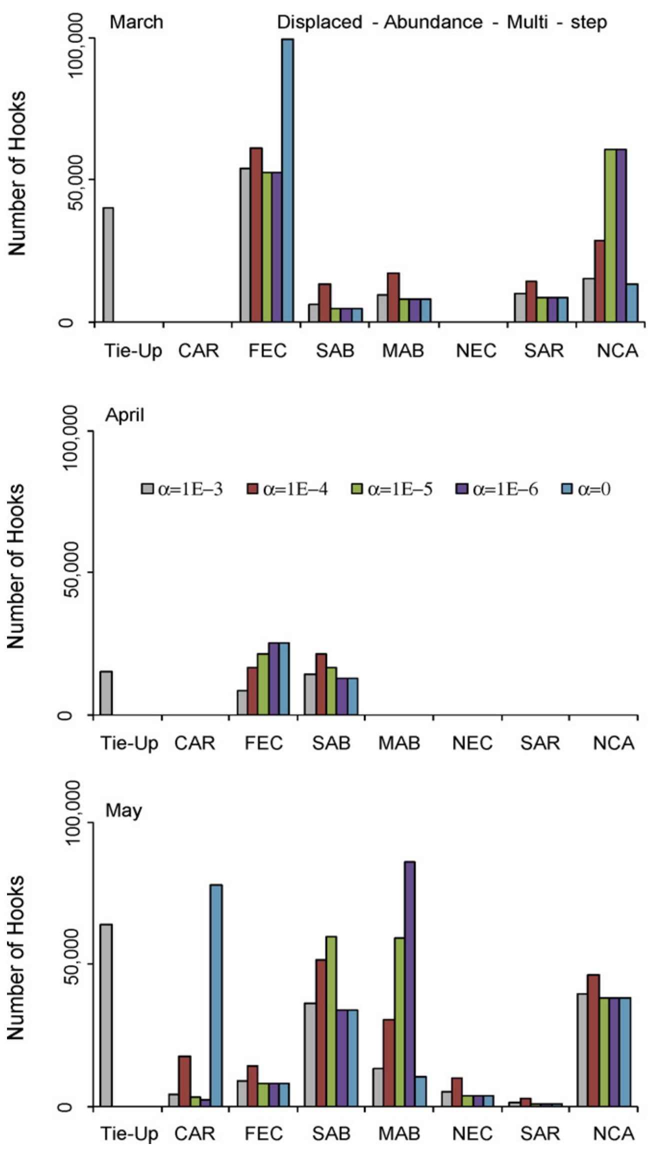

Fig. 4. The distribution of effort by area for the months of March–May using Multi-step Displacement with the Abundance model. The movement cost matrix uses $\lambda = 1$, $\gamma = 1$ (as in Table 2). Analyses were conducted for depletion rates (α's) which appear left-to-right in the graph in the order that they are listed in the legend.

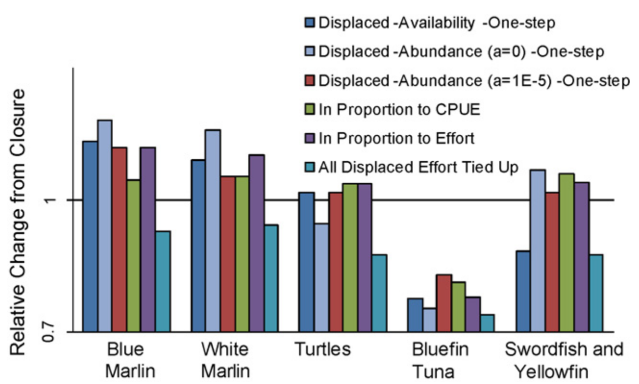

Fig. 5. Relative change in the number animals caught plus discards (both alive and dead, for all year) with a closure of the Gulf of Mexico, March–May relative to no closure, using US pelagic longline observer data 2001–2003. The movement cost matrix uses $\lambda = 1$, $\gamma = 1$ (as in Table 2). Methods appear left-to-right in the graph in the order that they are listed in the legend.

ers' decisions (and the time scale of the evaluation) are expected to occur in multiple moves or in a single move. In most instances, the time scale of closure evaluations would imply that fisher decisions would be a one-time move. Additionally, if there is a one-time move it is less likely that the Redistribution model would be appropriate. For example under the One-step approach it is unlikely that fishers in the NEC would transfer their effort to another area because of GOM closures.

The cost matrix (Table 2) was calculated assuming near equilibrium conditions and that the cost was symmetric. While alternatives were tested (Tables 4–6) which rescaled costs and introduced asymmetry, the alternatives still maintained the basic ordering of Table 2. It was noted that distance between areas is not the only indicator of cost. Nevertheless, Table 2 results in some non-intuitive costs. For example movement costs from the GOM to the NCA were lower in May than from the GOM to FEC (Table 2). As fishing is an economic endeavor driven by cost and benefits, a formally estimated cost matrix is important in performing closure analyses and would alter the results obtained from an approximated cost matrix. Additionally, the threshold CPUE, L, is governed by a suite of economic factors and it too would benefit from formal analyses. Moreover, changes in economic conditions due to changes in factors such as fuel prices or interest rates on loans would diminish the usefulness of using previous CPUEs as indicators of L or V_{ij}. The relative cost matrices used here is based upon the expectation of CPUE of a fisher moving to a new area. But, this does not address the variability in CPUE that the fisher is facing. Variability may be translated into the risk associated with a move. Therefore an alternative to Table 2 might be to base relative costs on the expected CPUE plus a multiple of the standard deviation. This would avoid situations like the SAR in May (Table 1) where mean CPUE is similar to that in with other areas, but since the sample is small, the variation in CPUE is larger.

In the absence of economic analysis, the question remains whether an indicator of relative cost based upon CPUE can be useful. In our example changing the scale and symmetry does not alter the effort distribution very much in most cases. Additionally, this approach is compatible with management strategy evaluations (MSEs) in which robust management procedures are developed by extensive simulation testing of management options against an operating model of the fish and fishery (Smith et al., 1999). The estimation of redistribution of effort and the consequences for bycatch and other objectives can be fully automated within an MSE. Importantly, the robustness of ad hoc estimations of the cost matrix can be tested. Nevertheless, constructing a cost matrix (even if it is based upon CPUE) should include an element-by-element evaluation.

The suitability models used herein imply that CPUE deteriorates when additional effort moves to an area. If this is not the case, then this is equivalent to the Abundance model results with $\alpha = 0$. In that case, effort moves to the area in which CPUE/cost is the highest. In many instances this variation may be more applicable. Furthermore, it was assumed that effort could not shift outside of a time period (i.e. that effort could not be increased just prior to the closure or just after reopening, or during some other period). As there were no temporal modifications to the models, we assumed that the duration of the closures was sufficiently long that the transit time was insignificant. It is possible, however, to restructure the models to include a temporal dimension to movement costs and to the CPUE matrix.

There are limitations in applying these methods; foremost in these limitations is the spatial scale of the data that are available. These methods (or any methods using CPUE data) assume that CPUE differences between areas are both predictable and meaningful. This is especially relevant when examining closures with small spatial scales. For example, with a small MPA, having CPUE information at the boundaries is extremely important. Implicitly it is assumed that the fish do not move greatly within a spatio-temporal stratum. If they do, then the benefits of a closure would be negated regardless of which model used. As the models were implemented here, it was assumed that effort could not shift temporally, i.e. that effort could not be increased just prior to the closure or just after reopening. Nor could effort shift to another month. It is possible to restructure the models to include a temporal dimension to movement costs and the CPUE, but that was not done here. Without temporal modifications to the models, the results could be expected to apply to closures that are long enough such that the temporal movement of effort is insignificant.

It is important to note that all the models explored here (including the IFD-based models, proportional redistribution methods *and* the FMP method) are static analyses. This implies that the CPUE being measured during the simulation directly relates to the CPUE at the time the closure is implemented, and the equilibrium CPUE will be constant throughout the duration of the regulatory program. The implication of this is that the underlying abundance of fish by area is not changing. If this is so, then more detailed MSE evaluations based upon stock assessments might be required. While this is a factor to be considered in designing a closed area regime, all impact evaluations assume stationarity of a model to make predictions. Therefore, an adjunct to any design of a closed area should include a monitoring program to allow one to empirically test the effectiveness of the closure and to estimate changes in the underlying fish population levels and in the fishers' effort redistribution behavior.

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