ICES Journal of Marine Science, 62: 1150–1167 (2005)
doi:10.1016/j.icesjms.2005.04.005

Effort distribution and catch patterns adjacent to temperate MPAs

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Murawski, S. A., Wigley, S. E., Fogarty, M. J., Rago, P. J., and Mountain, D. G. 2005. Effort distribution and catch patterns adjacent to temperate MPAs. – ICES Journal of Marine Science, 62: 1150–1167.

We evaluated the spatial distribution of otter trawl fishing effort and catches resulting from the imposition in 1994 of year-round and seasonal groundfish closed areas off the NE USA. Vessel locations were available from logbooks, vessel monitoring system (VMS) data from many of the largest vessels, and from observer records. There was high spatial coherence between VMS- and observer-derived trawling locations. Prior to establishment, 31% of trawl effort (1991–1993) occurred within the 22 000 km^2 of area that would eventually be closed year-round. In 2001–2003 about 10% of effort targeting groundfish was deployed within 1 km of the marine protected area (MPA) boundaries, and about 25% within 5 km. Density gradients, consistent with spill-over from MPAs, were apparent for some species. Average revenue per hour trawled was about twice as high within 4 km of the boundary, than for more distant catches, but the catch variability was greater nearer closed area boundaries. Seasonal closed areas attracted more fishing effort after opening than prior to closure even while average cpue was the same or lower. Spatial resolution of traditional data sources (e.g., logbooks) was too crude to discern detailed MPA-related effects, as revealed by high-resolution vessel positions from VMS and catch data obtained by observers.

Keywords: marine protected areas, MPA, observer data, spill-over, vessel monitoring system, VMS.

Received 11 November 2004; accepted 19 April 2005.

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Introduction

Marine protected areas (MPAs) and other forms of spatial closures are increasingly common components of management programmes for living marine resources (NRC, 2001; Ward *et al.*, 2001). The use of MPAs has been primarily advocated for protection of sensitive marine habitats and associated fauna, reflecting their predominant use in tropical ecosystems (Roberts *et al.*, 2001; Willis *et al.*, 2003; Ashworth and Ormond, 2004). Increasingly, these management tools have been proposed and implemented in temperate and boreal ecosystems for use in achieving traditional fishery management goals, for limiting by-catches, and for habitat protection (Horwood *et al.*, 1998; Piet and Rijnsdorp, 1998; Frank *et al.*, 2000; Fisher and Frank, 2002; Gell and Roberts, 2003; Sissenwine and Murawski, 2004). While MPAs have been proposed and implemented in many ecosystems throughout the world, commensurate studies of their biological impacts and, in particular, the spatial adaptations by fishers to the imposition and placement of such closures, have been few (Sanchirico and Wilen, 2002; Smith and Wilen, 2003; Wilcox and Pomeroy, 2003). These adaptations can be critically important to the achievement of management objectives, particularly if fishing effort becomes inappropriately concentrated near the boundaries owing to the effects of the closures (Botsford *et al.*, 2003; Halpern and Warner, 2003; Halpern *et al.*, 2004).

1054-3139/$30.00

In this paper, we provide analyses of changes in the patterns of fishing effort associated with year-round and seasonal fishery closures off the northeast USA, adopted over a decade ago (Figure 1). The closed areas are unique because of their size (more than 22 000 km^2 in year-round closed areas, and a greater area in seasonal closures), and because the closed areas include most of the productive fishing grounds for New England groundfish species. The system of closed areas was originally adopted to help conserve and rebuild depleted stocks of gadoids, flounders, and other species regulated under the USA Magnuson-Stevens Fishery Conservation and Management Act (Murawski *et al.*, 2000). Previous studies of these areas documented variable impacts, including the build-up of biomass of a few species in several of the year-round closed areas (Fogarty, 1999; Murawski *et al.*, 2000, 2004; Link *et al.*, 2005). There is also limited evidence for "spill-over" of biomass of harvestable sized animals from closed to open areas, for haddock, *Melanogrammus aeglefinus*, and yellowtail flounder, *Limanda ferruginea*, and a few other species (Murawski *et al.*, 2004). The most compelling biological effects of the year-round closures on Georges Bank (Figure 1) have been for sessile animals, and in particular for populations of sea scallop, *Placopecten magellanicus* (Murawski *et al.*, 2000).

Objectives

Evaluating changes in effort distribution and concentration over time was a primary objective of the present study. Analyses undertaken in this study are aimed at answering several important questions regarding the impacts of MPAs and seasonal closures in New England waters. In particular: has effort become concentrated at the boundaries of the closed areas? Is there more complete evidence of targeting of potential spill-over of stock biomass from the closed areas? How has the placement of year-round closures influenced the spatial distribution of catches and associated revenues? What are the effects of seasonal closures on the concentration of fishing effort, and catch rates? And how does the presence of the year-round closures affect the spatial choice dynamics and other aspects of fisher behaviour?

To address these and ancillary questions, we analysed fishing effort, catch, and revenue data available from port sampler interviews (1991–1993) vessel trip reports (VTR = logbooks, 2003), vessel monitoring systems (VMS = satellite tracking, 2003), and results of fishery observer sampling (2001–2003). In particular, we evaluate the catch per unit of effort (cpue) for various species and combinations and revenue per unit effort ($pue) as potential explanatory variables describing targeting of

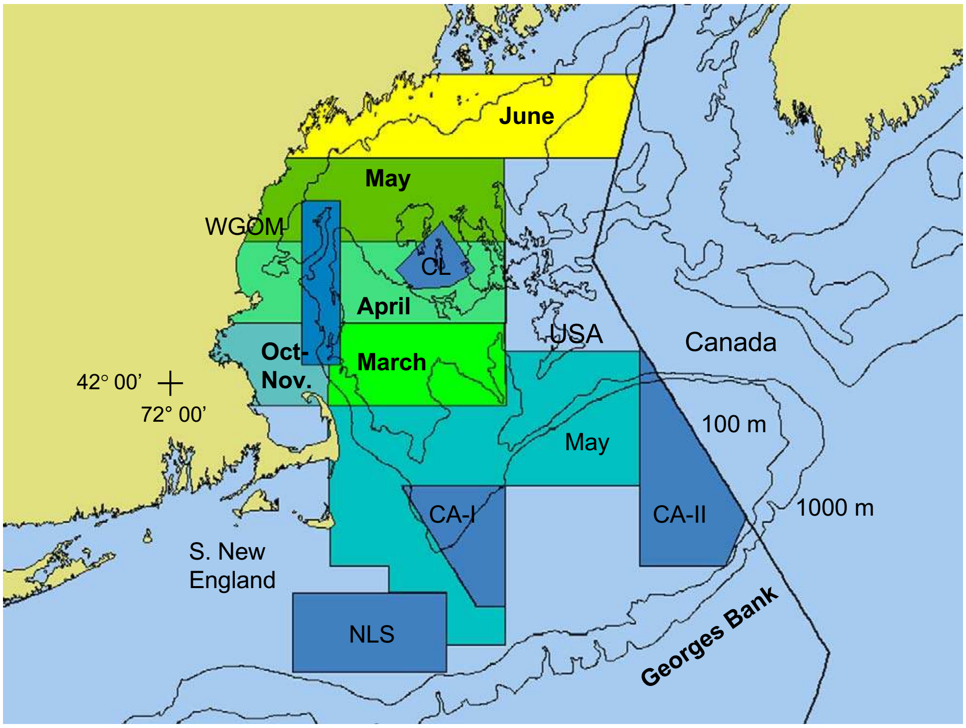

Figure 1. Year-round and seasonal closed areas for groundfish protection off the northeast USA. Coding is: CA-I = closed area I, CA-II = closed area II, NLS = Nantucket Lightship, WGOM = Western Gulf of Maine, CL = Cashes Ledge. Seasonal closure boundaries are partially obscured by various months.

fishing effort, particularly in relation to distance from the edges of MPAs.

Material and methods

Closed areas, data sets, and calibrations

Description of closed areas

The five year-round closures in New England waters (Figure 1, totalling about 22 000 km^2) were originally sited to protect and restore overfished groundfish resources. The three southern areas [Closed areas I and II on Georges Bank (CA-I and II) and the Nantucket Lightship Area in Southern New England (NLS)] were closed year-round to all fishing gears capable of retaining groundfish, beginning in 1994 December. The Western Gulf of Maine closure (WGOM) was added in 1996. An additional year-round closed area is located in the central part of the Gulf of Maine (Cashes Ledge), and was closed from 1998. Since closure, the only gears that have been allowed in the reserves include lobster traps, midwater trawls (for Atlantic herring, *Clupea harengus*), and some limited dredge fishing for sea scallops. In 2004, some groundfishing was allowed in CA-II, but the current analyses utilize data only through 2003.

Nearshore, seasonal or "rolling" closures (Figure 1) have been part of the groundfish management plan since the 1990s. Seasonal closed areas in nearshore waters of the Gulf of Maine have multiple objectives, but are primarily intended to limit exploitation on populations of Atlantic cod, *Gadus morhua*, and harbour porpoise, *Phocoena phocoena*, which are taken as bycatch in demersal gillnet fisheries in the Gulf of Maine. Additional seasonal closures were added to assist in reducing fishing mortality on Gulf of Maine and Georges Bank groundfish stocks. The areal extent of the rolling closures illustrated in Figure 1 is partially obscured, and actual boundaries of each monthly closure can be found at: http://www.nero.noaa.gov/nero/regs/infodocs/info4.pdf). In particular, we consider patterns of effort and cpue for two of the areas: the square indicated by "October–November" (designated as rolling closure 5, or RC-5), and the square west of the WGOM year-round closure and north of RC-5, designated as RC-4&2 (see "Effects of Seasonal Closures" below).

Pre-1994 effort data

Evaluating changes in effort distribution and concentration over time was a primary objective of the present study. Unfortunately, when more strict management regulations (including the imposition of year-round closed areas) were adopted in 1994, the system of routine effort and catch data collection changed as well. Prior to 1994, these data were collected primarily through a system of "port agent" interviews wherein experienced samplers gathered catch, effort, and positional data through voluntary submissions from cooperating fishers. Port agent-derived data for the pre-1994 period are illustrated in Figure 2. These data are the quantities of trawl-fishing effort (in days fished) aggregated to 10′ squares. These data are the finest spatial resolution available. Some of the data collected through this system could not be assigned a position to 10′ square, and were thus aggregated to appropriate quarter-degree square based on typical effort patterns. This accounts for the regular pattern every third 10′ square in the 1991–1993 data (Figure 2). These data were previously evaluated by Fogarty and Murawski (1998), illustrating that prior to imposition of the year-round closed areas on Georges Bank, these areas were heavily fished by trawlers targeting various groundfish stocks. Based on the centre points of various 10′ squares, we calculated that 31% of the total trawl-fishing days at sea expended in New England waters during 1991–1993 were located within the "footprints" of the five year-round closed areas.

Post-1993 effort data

After the imposition of mandatory catch and effort reporting for the New England multispecies (=groundfish) fishery in 1994, the data collection system was changed to one based on submission of vessel and processor trip reports. Each vessel was required to submit a vessel trip report (VTR = logbook), indicating species caught, position, and other data. Each processor was required to submit logs indicating quantity of groundfish bought, and from whom. Fishers were required to fill out separate log pages for each statistical reporting area fished, and were asked for more precise location data. Given the variable quality of these data, these too were aggregated into 10′ squares, for the purpose of comparison with earlier pre-closure effort patterns and other sources of contemporary positional data. Not all fishing effort could be assigned a position under the current system, and some positional data were suspect, given the self-reported nature of the data and the lack of independent verification. Current (2003) spatial patterns of fishing effort (days fished by trawlers) reported under the multispecies VTR program are illustrated in Figure 3.

In addition to VTR data, two other data sources are available to discern spatial distribution of effort and catch rates of trawlers. A number of the largest groundfish fishing vessels are equipped with a vessel monitoring system (VMS) that tracks vessel position while fishing. This is a voluntary program instituted primarily for the purpose of counting days-at-sea usage, as these vessels are limited by the number of days at sea when fishing for groundfish. The VMS system is fully automated, and queries each vessel hourly. The data set generated from the VMS includes vessel position, vessel permit number, and two derived variables – the calculated vessel heading (e.g. direction from previous location to the current location) and the corresponding vessel speed (in knots). The "raw" data set includes all vessel positions, regardless of vessel speed. To filter the VMS data for vessel positions so as to ascertain

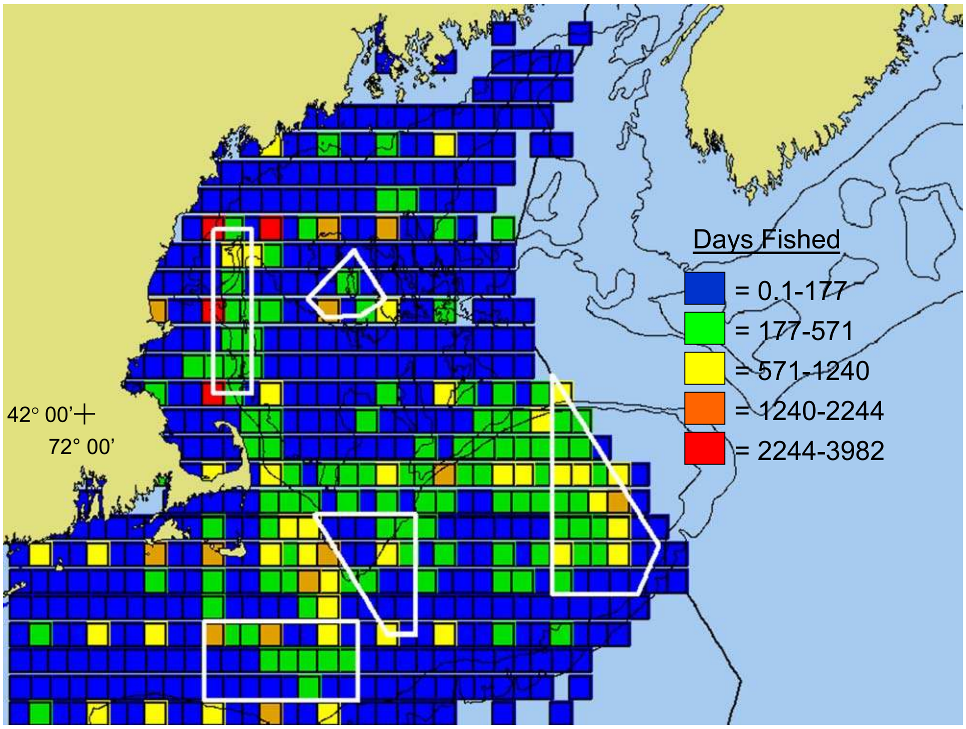

Figure 2. Otter trawl fishing effort distribution during 1991−1993 off the northeast USA, prior to closure of areas outlined in white. Data were obtained from voluntary port agent interviews. Data are aggregated to 10′ or quarter-degree squares. A total of 31% of total effort was within the footprint of the year-round closed area boundaries.

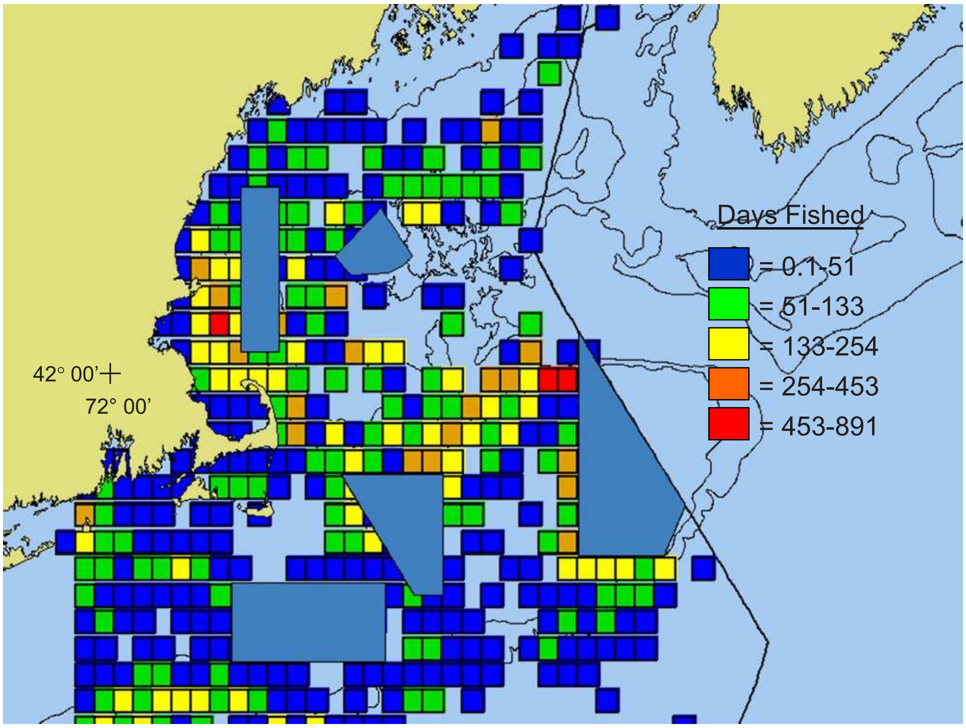

Figure 3. Otter trawl fishing effort distribution during 2003 off the northeast USA, prior to closure of the areas indicated in blue. Data were obtained from mandatory vessel trip reports (log books). Data are aggregated to 10′ squares.

positions where trawling was occurring, we evaluated towing speeds based on observed tows (see description of observer data below). We found that for 94.4% of the otter trawl tows observed, the towing speed was 3.5 knots or less. Accordingly, we used 3.5 knots as a threshold to indicate when trawling was occurring, and eliminated vessel positions with speeds in excess of this value. There are likely some vessel locations where speeds are below 3.5 knots and trawling is not occurring (e.g. due to breakdowns or other causes), and vice versa, vessel speeds in excess of 3.5 knots where trawling is occurring. However, both of these situations are likely a small portion of the total data set. The VMS data for 2003 are illustrated in Figure 4. These data are aggregated to 1′ squares for the purpose of data manipulation, as the filtered data set includes 113 338 vessel positions in 14 208 1′ square locations.

The third source of position and ancillary catch data was from fishery observers aboard multispecies trawl vessels (Figure 5). Coverage in the observer program has increased significantly since 2001 owing to a court order to observe at least 5% of the total groundfish catch. In 2001, there were 1484 otter trawl tows from which observer data were available, increasing to 3006 tows in 2002 and 5640 in 2003, for a 3-year total of 10 130 (Figure 5). Some of the tows recorded were actually unobserved, and only kept catch and tow positions were available. For cpue analyses (e.g. catches including kept and discarded catch), we used 1423, 2732, and 5128 tows, respectively, during the years 2001−2003, for a total of 9283.

Comprehensive data are collected from observed tows (Murawski, 1996), and include beginning and end points of each haul, depth, haul duration, mesh size of net used, target species, and catch (kept and discarded, by species). Additional positional, gear, and economic information is included for each tow or trip observed, as appropriate. From these data we developed a single record for each tow for further analysis. Each record included the year, month, week, day of the year, mesh size, hours trawled, the gross tonnage (GRT) of the vessel, tonnage class (class 2 = 5−50, class 3 = 51−150, class 4 = 151 + GRT), primary and secondary target species, start and end locations, number of species caught, total kg (kept + discard) of all species, total kg of groundfish species (see below), total kept catch, and catch (kept + discarded) for each of the 13 species listed below.

In addition to these primary variables, additional variables were computed and included in the catch record. The total value (US$) of the kept portion of the catch was determined by applying the average weekly price per kg, by species, paid dockside, to the kept catch in weight by species in each tow (Table 1). A number of the analyses of observer data involve computing distances of the tows from closed area boundaries and between sequential tows. We used ArcView® GIS software to compute these distances,

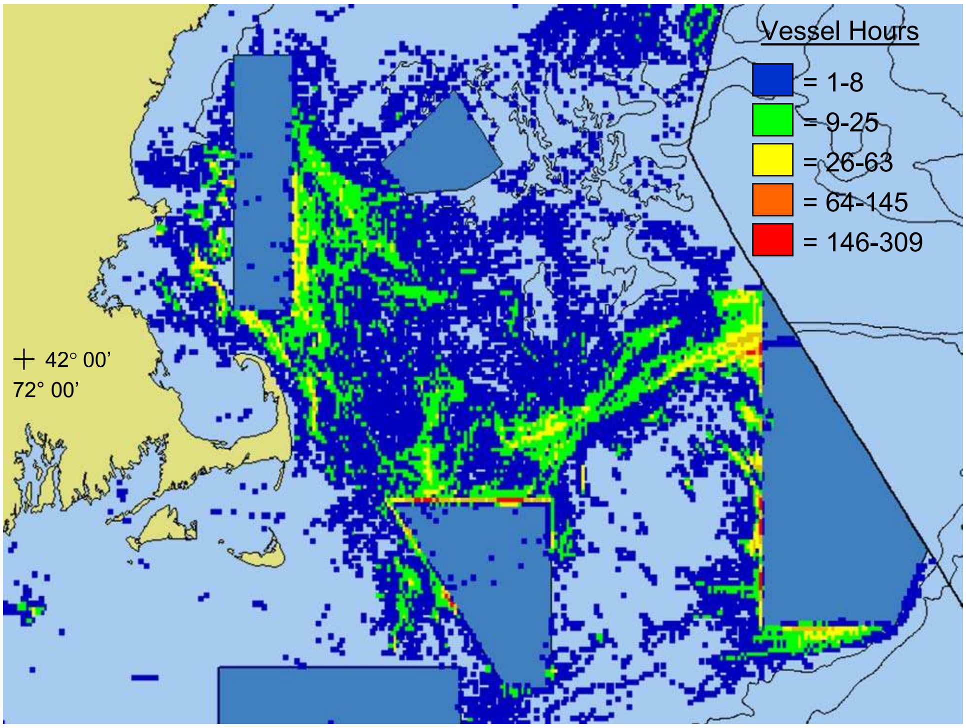

Figure 4. Otter trawl fishing vessel effort off the northeast USA, 2003. Data were obtained from vessels using VMS (vessel monitoring systems) using satellite tracking. Locations are plotted only for vessel speeds ≤ 3.5 kn. Data are aggregated to 1′ square.

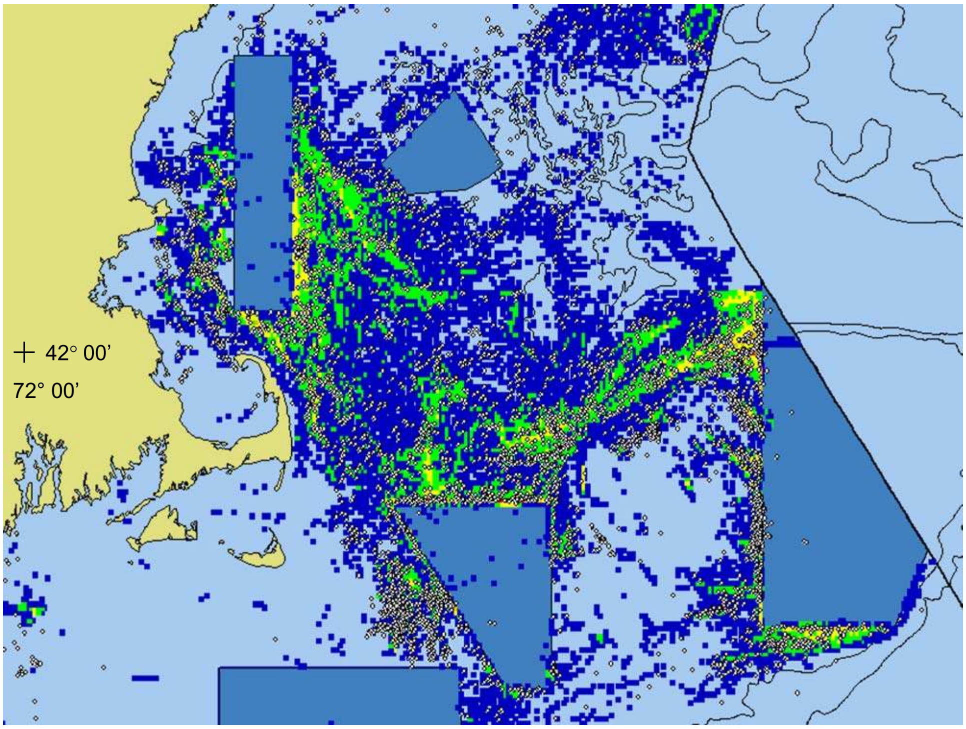

Figure 5. Locations of observed otter trawl tows off the northeast USA in 2003 (open circles) in relation to VMS effort locations (Figure 4). Plotted locations are the starting positions of each observed tow. Total number of observed tows = 5106.

and appended them to the catch records: distance (km) from the end of the last tow to the beginning of the current tow, distance from the current tow to the next tow, minimum distance from the tow start location to each of the boundaries of the five year-round closures, and the minimum distance to any one of them. We also used ArcView® to determine the membership of each tow within the "footprints" of each of six seasonal, or "rolling" closures (e.g. tows that are within the boundaries of the seasonal closures, at times when they are open, Figure 1). The data are explored in detail for two such rolling closures.

Table 1. Average catch rates and associated characteristics of catches resulting from observer sampling of otter trawl catches off the NE USA, 2001–2003. Catch rates are standardized to account for vessel size class differences. Number of species per tow represents all taxa identified by observers, not just the groundfish species.

Characteristic	Mean	s.d.	CV
All species combined, kg h^{-1}	257.90	676.05	2.62
Groundfish combined, kg h^{-1}	131.45	284.02	2.16
$ per h	336.84	585.76	1.74
h per tow	3.715	1.610	0.43
Number of species per tow	10.00	3.138	0.31

Species selected for analysis from the observer data included: monkfish (goosefish), *Lophius americanus*, Atlantic cod, winter flounder, *Pseudopleuronectes americanus*, witch flounder, *Glyptocephalus cynoglossus*, yellowtail flounder, American plaice, *Hippoglossoides platessoides*, haddock, Acadian redfish, *Sebastes fasciatus*, red hake, *Urophycis chuss*, white hake, *Urophycis tenuis*, pollock, *Pollachius virens*, spiny dogfish, *Squalus acanthias*, and silver hake, *Merluccius bilinearis*.

Cpue standardization

We used cpue data from observed trawl tows to evaluate spatial patterns of fish density and catch rates. However, such data are potentially confounded by differences in catchability owing to variation in vessel characteristics including size, horsepower, and differences in fishing gear, crew, and skipper effects, etc. Earlier analyses (Murawski *et al.*, 2004) indicated that catch rates differed little for vessel size classes 3 and 4, but that class 2 vessels had lower catchabilities than the larger vessels. Part of this effect was due to spatial differences as class 2 trawlers rarely fish offshore on Georges Bank, and are primarily limited to coastal areas of the Gulf of Maine.

We conducted a series of calibration studies with the objective of standardizing effort among the three vessel size classes to account for vessel size differences. Three sets of such analyses were conducted using general linear models

(GLM), implemented in SAS (Tables 2 and 3). Main GLM effects were year, vessel size class, and area. Standard categories for each were year = 2003, vessel size class = 3, and area = Georges Bank. GLM models used ln kg tow^{-1}, with zero catches eliminated from the analysis. Zero values were eliminated because most species null catches reflected "structural" effects rather than sampling variability, owing to the limits of depth and geographical distributions of various species. With an average tow duration of 3.7 h (Table 1), there was high likelihood of catching at least one individual of the 13 relatively abundant species listed above, if fishing occurred within the species' habitat range. Analyses were conducted using, as the response variable, total (all species) catch per hour towed (catch = kept + discard; Table 2). Additionally, we conducted similar analyses for the sum of the 13 species identified above, termed groundfish cpue (Table 3). Lastly, we conducted GLM analyses for each of the 13 species, year, and area combinations. To estimate appropriate linear calibration coefficients, we re-transformed the natural log of the parameter estimates by adding half of the estimated variance to the parameter estimates for vessel size classes, and taking anti-logs.

Table 2. General linear model (GLM) results for calibration of otter trawl cpue for vessel size class differences. Dependent variable is the ln kg per hour towed for all species caught. The abbreviation tc is tonne class. Lower table provides re-transformed calibration coefficients for tonne classes 2 and 4. GOM is Gulf of Maine, GB is Georges Bank.

r^2	CV	Root MSE	Mean ln cpue all species
0.0616	0.1813	0.9013	4.9722

Source	d.f.	TYPE-III SS	Mean square	F	Pr > F
Year	2	60.49	30.24	37.23	<0.0001
tc	2	11.27	5.64	6.94	0.0010
Region	1	187.63	187.63	230.95	<0.0001

Parameter		Estimate	s.e.	t value	Pr	Retransform
Intercept		5.1375	0.0166	308.59	<0.0001	170.312
Year	2001	−0.2418	0.0284	−8.52	<0.0001	0.786
Year	2002	−0.0199	0.0218	−0.92	0.3598	0.980
Year	2003*	0.0000				
tc	2	−0.1344	0.0367	−3.66	0.0003	0.875
tc	4	0.0015	0.0208	0.07	0.9430	1.002
tc	3*	0.0000				
Region	GOM	−0.4106	0.0270	−15.20	<0.0001	0.664
Region	GB*	0.0000				

*Standard cells.

Table 3. General linear model (GLM) results for calibration of otter trawl cpue for vessel size class differences. Dependent variable is the ln kg per hour towed for groundfish species caught. The abbreviation tc is tonne class. Lower part of table provides re-transformed calibration coefficients for tonne classes 2 and 4. GOM is Gulf of Maine, GB is Georges Bank.

r^2	CV	Root MSE	Mean ln cpue groundfish
0.011	0.2188	0.9559	4.3657

Source	d.f.	Type-III SS	Mean square	F	Pr > F
Year	2	9.67	4.84	5.30	0.0050
tc	2	32.65	16.33	17.90	<0.0001
Region	1	7.58	7.58	8.31	0.0040

Parameter		Estimate	s.e.	t value	Pr	Retransform
Intercept		4.3362	0.0177	245.38	<0.0001	76.4318
Year	2001	0.0676	0.0301	2.25	0.0247	1.0705
Year	2002	0.0663	0.0231	2.87	0.0041	1.0689
Year	2003*	0.0000				
tc	2	−0.1272	0.0389	−3.27	0.0011	0.8813
tc	4	0.0970	0.0220	4.40	<0.0001	1.1021
tc	3*	0.0000				
Region	GOM	−0.0826	0.0286	−2.88	0.0040	0.9211
Region	GB*	0.0000				

*Standard cells.

Results

Vessel size calibration coefficients indicate that class 2 vessels generally have lower catchabilities than the two other vessel size classes, and these differences are consistent irrespective of response variable considered. For all species catch, re-transformed coefficients for classes 2 and 4 were 0.875 and 1.002, respectively (Table 2). For groundfish catches, these coefficients were 0.881 and 1.102 (Table 3). Average relative calibration coefficients computed for individual species were 0.855 and 1.892 for vessel classes 2 and 4, respectively. Based on these results, we used re-transformed vessel size class calibration coefficients estimated for the "all species" catches, dividing the raw cpue of each tow by the appropriate coefficients: class 2 = 0.875, class 3 = 1.000, class 4 = 1.002. These calibration coefficients were applied to all species, groundfish species and individual species cpue values, including $pue data.

Effort displacement and aggregation in relation to closed area boundaries

Has trawl-fishing effort become concentrated at the closed area boundaries as a result of the imposition of the year-round closures? Inspection of the 1991–1993 and 2003 fishing effort data (Figures 2 and 3) indicates substantial changes in the distribution of trawl-fishing effort before and after implementation of the closed areas. In particular, proportionally more effort now occurs along the southern edge of CA-II, along the northern edge of CA-I, and along the northern edge of Georges Bank from the NE corner of CA-I to the northern point of CA-II. Interestingly, the shallow area between CA-I and CA-II attracts relatively little trawl-fishing effort (even before the closures), and more effort now appears west of the WGOM closure in nearshore areas. Based on VMS data, there are clear concentration effects, particularly around CA-I and CA-II, and the western edge of WGOM (Figure 4). Most of the effort concentration around the Georges Bank areas appears to be within one to two 1′ squares. There appears to be little effort concentration around the NLS and CL areas, as revealed in all 2003 data sets, including observer data (Figure 5).

Concentration profiles for the various fishing effort data are summarized in Figure 6. These profiles provide the cumulative proportion of total effort as a function of distance to one of the five year-round closed areas. The distance measure used is the minimum calculated for each effort datum to each of the five year-round areas. Six different fishing effort data sets are plotted: (i) 1991–1993 port agent effort (aggregated to 10′ squares), (ii) 2003 VTR data (aggregated to 10′ squares), (iii) 2003 observer (sea sampling) data, (iv) 2003 VMS data (aggregated to 1′ squares), (v) 2002 observer data, and (vi) 2001 observer data. Most apparent in these profiles are the effects of aggregating data to 10′ or, in the case of VMS data, 1′ squares. The 2003 VTR data show some degree of increased concentration near the closed area boundaries, as compared with the 1991–1993 data, but the degree of aggregation appears too coarse to detect concentration effects on the order of 1–5 km. This effect can be illustrated by a simple example. If the edge of a 10′ square was aligned with the north or south boundary of a rectangular closed area, then the minimum distance from the edge of the closed area boundary to the mid point of the 10′ square is 5 nautical miles (e.g. in longitude). Thus, these observations of effort would be calculated as being 5 nautical miles or 9.3 km from the closed area boundary. The mid point of a 10′ square aligned along an east or west boundary of a rectangular closed area would be a minimum of 6.9 km from the closed area boundary (e.g. in latitude, for the areas under consideration). This aggregation effect contributes to the "stair-step" effect observed in the 10′ square data.

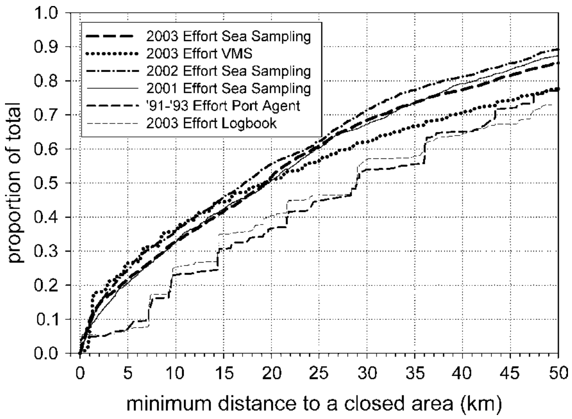

Figure 6. Cumulative distribution of fishing effort as a function of the minimum distance to any one of five year-round closed areas off the northeast USA. Data sets are plotted in Figures 2–5.

The more detailed (2001–2003) effort data series show a remarkable degree of consistency. All data series show that about 9–10% of the trawling effort occurs between 0 and 1 km of a closed area boundary, 20–27% within 5 km, and 50–55% within 20 km of a closed area. The VMS data appear slightly more concentrated at the boundary than observer data, while the 2003 VTR data appear less concentrated near the boundaries. These differences may be partially accounted for by differences in vessel sizes predominantly represented in the various data sets. VMS data come primarily from large class 3 and class 4 trawlers, which have a high degree of mobility and which may be more responsive to spatial variations in catch rates. Observer data include some class 2 vessels, which may concentrate in nearshore waters away from closed areas. In fact, the average distances from each tow to a closed area boundary by vessel size classes are: class 2 = 25.4 km, class 3 = 21.5 km, and class 4 = 21.8 km (based on 2001–2003 observer data). VTR data include some effort (particularly off Southern New England) directed to non-groundfish species, reflecting the somewhat lower concentration profile for these data, particularly at distances greater than a few km from closed area boundaries.

Overall there appears to be local concentration of effort at 0–5 km from the boundaries of closed areas I and II and to a limited extent WGOM. Prior to the areas being closed, about 31% of all effort and likely a higher proportion of groundfish effort was expended within the future closed area boundaries. There was no particular reason for this effort to occur necessarily at the future closed area boundaries. Thus, the recent concentration of 10–20% of effort within 5 km of the closures reflects the reallocation of effort from within the closed areas as well as any effort attraction owing to higher expected catch rates in the vicinity of the boundaries.

Spatial patterns of catch rates

Why is there a differential concentration of fishing effort associated with the boundaries of the year-round closures? In order to provide information to address this question we evaluated spatial patterns of catch rates (standardized for vessel size effects on catchability). If effort is concentrated near closed area boundaries it may be because there are real or perceived benefits in terms of increased catch rates associated with fishing near the closed area boundary (e.g. a density gradient, with highest catch rates closest to the boundary). If such density gradients exist, they may be the result of seasonal migrations of animals out of the closed areas, or the result of "spill-over" of animals that are concentrated within the boundaries of the closures (Figure 7).

Density-related spill-over is typified by a biomass or abundance gradient beginning at the boundary and declining as a function of increasing distance (Millar and Willis, 1999; McClanahan and Mangi, 2000; Russ *et al.*, 2003; Zeller *et al.*, 2003; Goni *et al.*, 2004). An important requirement for density-driven spill-over is that abundance within the closed area must be substantially greater than that outside the area on a continuing basis. Interpreting density gradients as evidence for spill-over thus requires sufficient understanding of seasonal and ontogenetic movements and the influences on distribution of environmental gradients and short-term environmental forcing. While a pattern of declining fish density as a function of distance from a closed area boundary is a necessary condition indicative of spill-over, it is insufficient evidence for concluding that such an effect is a consequence of the presence of the reserve. Analyses of some of the 2001 and part of the 2002 observer data indicated that density gradients existed for some species (e.g. haddock and yellowtail flounder), but not for most species (Murawski *et al.*, 2004). These initial analyses were based on 51 species-closed area combinations. Here we conduct a more comprehensive analysis of the spatial patterns of catch rates in relation to the distance to closed area boundaries, evaluating the potential for density-driven spill-over from the year-round closed areas.

Plots of cpue and $pue as a function of distance from closed area boundaries exhibit, in some cases, multiple

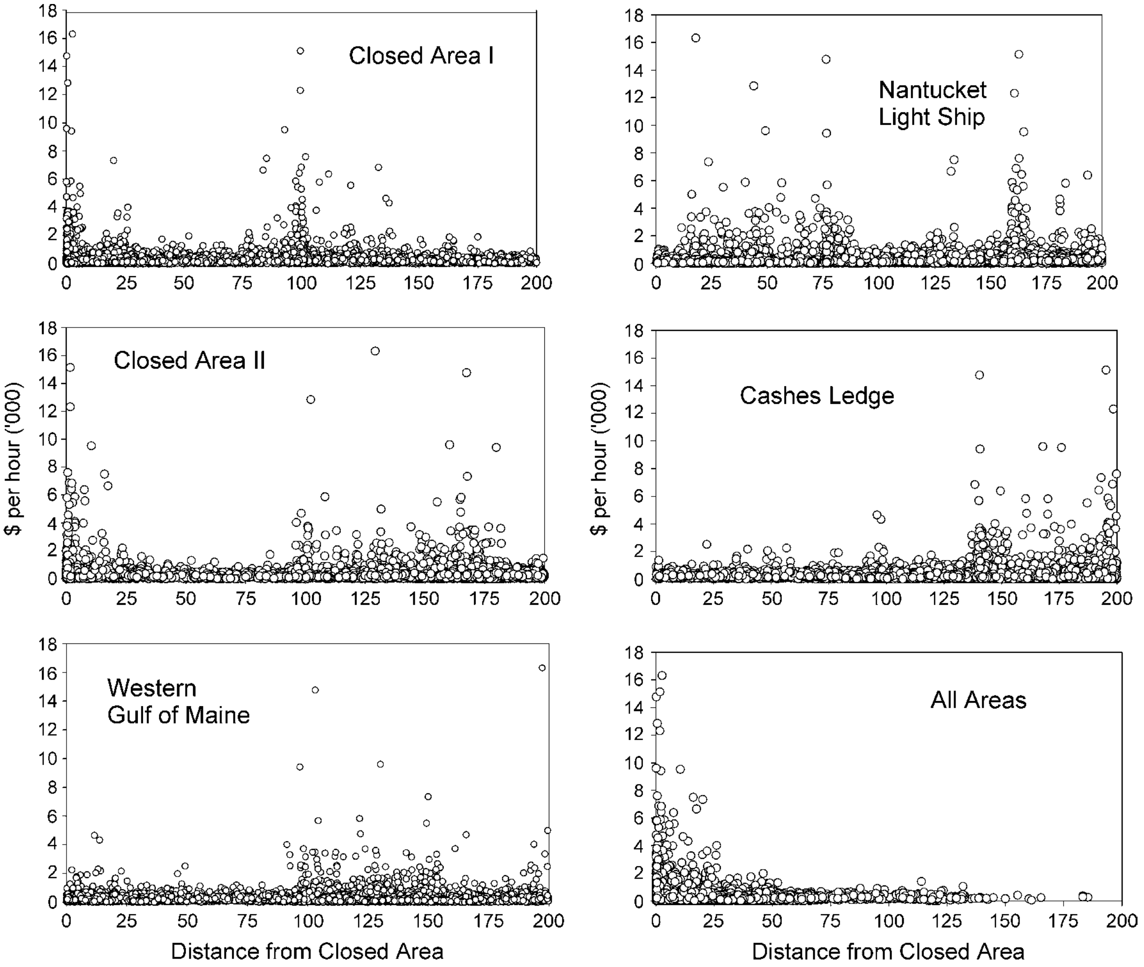

Figure 7. $pue ($ per hour towed, standardized for vessel tonnage class differences) as a function of distance from five year-round closed areas off New England, 2001–2003. Note that some high cpue values are located adjacent to CA-I and CA-II, but not near NLS, WGOM, or CL.

peaks associated with the various closed areas (Figure 7). In the case of \$pue, for example, the relationship between catch rate and minimum distance from closed area I shows modes at <20 km and at around 100 km (Figure 7). Similarly, data for closed area II show two abundance patterns at about the same spatial scales. There appears to be a density–distance relationship for closed areas I and II but for the NLS, WGOM, or CL closed areas there are only a few high catches in the vicinity of the closed areas. We limited the spatial extent of observations used to test density–distance relationships in some cases to avoid the potential for confounding spill-over effects from multiple closed areas (Table 4).

To test the hypothesis of a density gradient associated with closed area boundaries we computed the following density–distance relationship:

$$\ln(\mathrm{cpue}_{(i)}) = a + b \times \ln(X_{(i)}) + \epsilon_{(i)}, \qquad (1)$$

where, $\mathrm{cpue}_{(i)}$ = the catch per hour fished (kg) for tow i, $X_{(i)}$ is the minimum linear distance (km) between the closed area boundary and the start location of tow i, and a, b, and ϵ

Table 4. Analysis of selected combinations of observer data for potential spill-over effects from closed areas. Linear regression parameters and significance of ln (cpue, response variable) = a + b ln (distance) for various combinations of yearly data in relation to some or all year-round closed areas off New England. Response variables are cpue (kg or \$ per hour towed by trawlers, standardized for vessel class differences). Codes are: CA-I = closed area I, CA-II = closed area II, NLS = Nantucket Light Ship, WGOM = Western Gulf of Maine, CL = Cashes Ledge, p = probability of significance, n = number of samples used in regression. Numbers in italics indicate significant negative slopes.

Year	Response variable (cpue)	Closed area − distance to closed area (km)	a	b	p	n
2003	All species	All-all	5.249	*−0.092*	0.000	5 160
	Groundfish species		4.607	*−0.113*	0.000	5 082
	\$ per h		5.504	*−0.052*	0.000	5 085
2002	All species		5.179	*−0.065*	0.000	2 698
	Groundfish species		4.571	*−0.066*	0.000	2 687
	\$ per h		5.597	*−0.070*	0.000	2 691
2001	All species		4.882	*−0.044*	0.007	1 310
	Groundfish species		4.597	*−0.081*	0.000	1 290
	\$ per h		5.490	*−0.109*	0.000	1 309
2003	All species	CA-I ≤ 50	4.981	0.005	0.722	1 812
		CA-II ≤ 50	5.674	*−0.103*	0.000	1 290
		NLS ≤ 50	4.051	0.344	0.000	745
		WGOM ≤ 50	4.685	0.009	0.688	455
		CL ≤ 50	4.757	−0.009	0.780	549
		All ≤ 50	5.249	*−0.091*	0.000	4 524
2003	Haddock	CA-I ≤ 50	3.169	*−0.561*	0.000	1 017
2002			3.060	*−0.431*	0.000	810
2001			3.519	*−0.501*	0.000	410
2003	Yellowtail flounder	CA-II ≤50	3.145	*−0.343*	0.000	882
2002			3.680	*−0.698*	0.000	208
2001			2.154	0.351	0.014	82
2003	Monkfish	All ≤50	1.435	0.259	0.000	1 510
	Atlantic cod		2.442	0.001	0.937	3 548
	Winter flounder		2.826	*−0.104*	0.000	2 308
	Witch flounder		1.091	0.229	0.000	2 357
	Yellowtail flounder		2.431	*−0.173*	0.000	2 046
	American plaice		1.025	0.155	0.000	2 347
	Haddock		2.764	*−0.447*	0.000	2 760
	Red hake		0.071	*−0.235*	0.000	402
	White hake		1.188	0.142	0.000	1 234
	Redfish		0.828	−0.074	0.094	769
	Pollock		1.614	0.022	0.419	1 489
	Spiny dogfish		1.081	0.038	0.121	1 613
	Silver hake		−0.486	−0.047	0.082	929

are the intercept, slope, and error estimated from fitting the model, respectively. A significant negative slope would be consistent with a density gradient declining with distance from the closed area. This model was applied to all possible combinations of data (i.e., using catches for various individual species, species groups, and \$pue, associated with each of the five year-round closures, and all areas combined, Table 4; Figure 8). We computed a total of 279 linear regression models, some of which are summarized in Table 4. Overall there were 143 statistically significant regressions ($p < 0.05$), with 62 combinations exhibiting significant negative slopes. The average slope from the 279 analyses was 0.04, with the distribution of computed slopes reflecting a normal distribution centred near zero (Figure 8). Most of the negative slopes for individual species were associated with a few of the species and area combinations, and in particular haddock, yellowtail flounder, and winter flounder. All three of these species demonstrated increased densities in one or more of the closed areas, based on the results of research trawl surveys (Murawski *et al.*, 2004). Many of the aggregated species indices (e.g. all species catch, groundfish catch, and \$pue) that demonstrated significant negative slopes were driven by catches of one or more of these species. Haddock, in particular, demonstrated consistent evidence for a density gradient near CA-I in all three years of observer data (Table 4).

Overall, there were significant negative relationships between \$pue and distance from closed areas (Table 4), suggesting a reason for the differential concentration of effort near CAs I and II and WGOM since 1994. We explored these relationships in more detail to examine expected differences in benefits associated with fishing near the boundaries. Fishing effort (number of hours towed) is summarized in 1-km increments of minimum distance to any of the five year-round closures (Figure 9). These data show that there is a concentration of effort in the interval from 0 to 3 km from the closed area boundary, with the 0–1-km interval having nearly twice the effort as any other interval. The average \$pue is greatest in the four 1-km intervals nearest the boundary (averaging about \$470 h^{-1}), declining thereafter to an average of about \$273 per standard hour fished at distances from 10 to 50 km. Interestingly, while the average \$pue was relatively high near the edge of closed areas, declining thereafter, the variability in catch rates also declined significantly with increasing distance. The coefficient of variation of \$pue declined from nearly 2.0 at the closed area boundary to 0.75 at distances of 25 km and greater. There is thus a significant mean-variance trade-off associated with fishing near closed areas. This may partially explain why there is significant fishing effort away from closed areas boundaries, even though the average catches are lower there. Targeting of species not exhibiting significant spill-over is also a factor explaining effort allocated away from closed area boundaries.

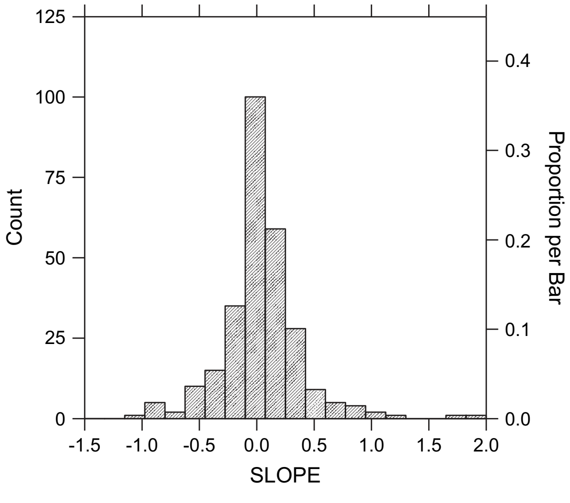

Figure 8. Distribution of calculated slopes from the relationship between log cpue and log distance (km) from five year-round closed areas off New England. A total of 279 regression models was fitted using various permutations of species, area, and year. Mean = 0.0433, s.d. = 0.3483, n = 279.

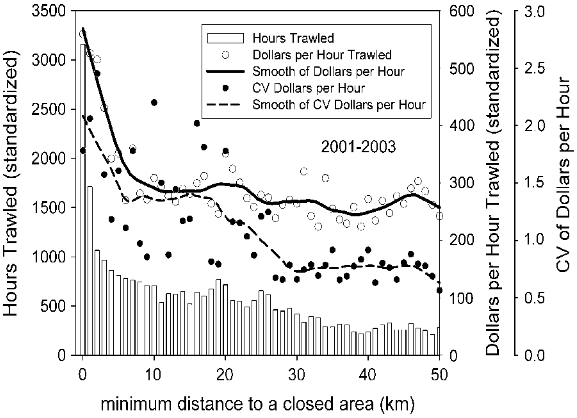

Figure 9. Distribution of observed fishing effort, \$pue (dollars per hour fishing) and CV of \$pue as a function of minimum distance to five year-round closed areas off New England, 2001–2003. Trend lines are lowess smooths using 20% of data.

These relationships of mean-variance of \$pue in relation to distances are driven by catch rates of a few species near three of the closed areas. Concentration profiles of various species catches in relation to distances to the closed areas show that a few of the species catches are highly concentrated near the boundaries, while others are not (Figure 10). In particular, haddock catches show extreme concentration associated primarily with closed area I. Overall, 42% of the USA catch of haddock was taken within 1 km of the closed areas, with 73% of haddock catches within 5 km. Other species showing hyperconcentration include yellowtail flounder and winter flounder.

Table 5. Results of binary logit models describing the probability of otter trawl tow locations off the northeast USA in 2003 being moved >10 km from the preceding tow within a fishing trip. Independent variables assessed were ln dollar value of retained catch in the previous tow, ln kept catch (kg) in the previous tow, log distance (km) from the nearest year-round closed area, and tonnage class identifiers (class 2 = 1−50 GRT, Class 3 = 51−150 GRT, Class 4 = 151 + GRT). Odds ratio is the factor by which the odds of a response changes when the independent variable increases by one unit. If the confidence interval of the odds ratio includes 1.0, the factor is not considered significant.

Binary category choices	Number of observations
0 (movement ≤ 10 km from previous tow = REFERENCE)	4 345
1 (movement > 10 km from previous tow = RESPONSE)	818
	Total = 5 163

Log likelihood: −2139.553

Parameter	Estimate	s.e.	t-ratio	Pr
1 CONSTANT	1.872	0.236	7.941	0.000
2 ln_DOLLARS	−0.260	0.076	−3.442	0.001
3 ln_KEPT	−0.294	0.080	−3.666	0.000
4 ln_DIST_CA	−0.026	0.025	−1.057	0.290
5 TON_CLASS_2	−0.344	0.163	−2.107	0.035
6 TON_CLASS_3	−0.252	0.082	−3.077	0.002

		95.0% bounds	
Parameter	Odds ratio	Upper	Lower
2 ln_DOLLARS	0.771	0.894	0.665
3 ln_KEPT	0.745	0.872	0.636
4 ln_DIST_CA	0.974	1.022	0.929
5 TON_CLASS_2	0.709	0.976	0.514
6 TON_CLASS_3	0.778	0.913	0.662

Model prediction success:

	[Predicted choice]		
Actual choice	Response	Reference	Actual total
Response	165.466	652.534	818
Reference	652.534	3 692.466	4 345
Predicted total	818.000	4 345.000	5 163
Proportion correct	0.202	0.850	
Total proportion correct:			0.747

Some species exhibit concentration profiles similar to the effort distribution profile, indicating neutral concentrations, especially Atlantic cod and pollock. At the other extreme, species such as witch flounder, white hake, and monkfish are concentrated primarily at distances well beyond the closed area boundaries.

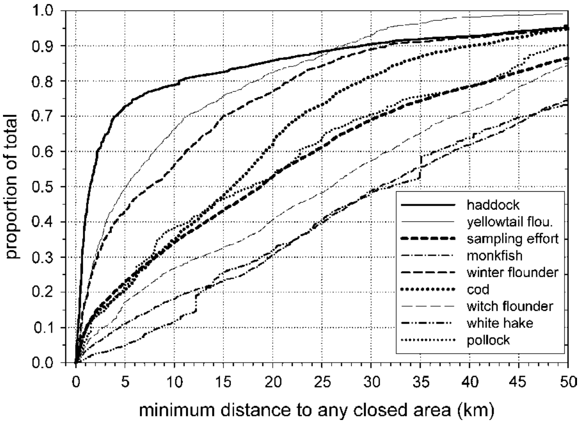

Figure 10. Cumulative proportions of catches and observed otter trawl fishing effort as a function of minimum distance to five year-round closed areas off New England. Data are from observed otter trawl tows.

MPAs and spatial choice

How does the presence of year-round MPAs influence the spatial choices of where to fish during trips? We used tow-by-tow data within each observed otter trawl trip sampled in 2003 to examine changes in the location of sequential trawl tows and the factors that bear on tactical decisions associated with changing fishing areas. We examined a variety of potential explanatory variables including catch weight, catch revenue, proximity to a closed area boundary, and other biological and economic considerations (Table 5; Figures 11 and 12). The objective of these analyses was to investigate relationships among these variables, rather than to develop a comprehensive bio-economic evaluation of effort allocation (Holland and Sutinen, 1999, 2000; Hutton *et al.*, 2004).

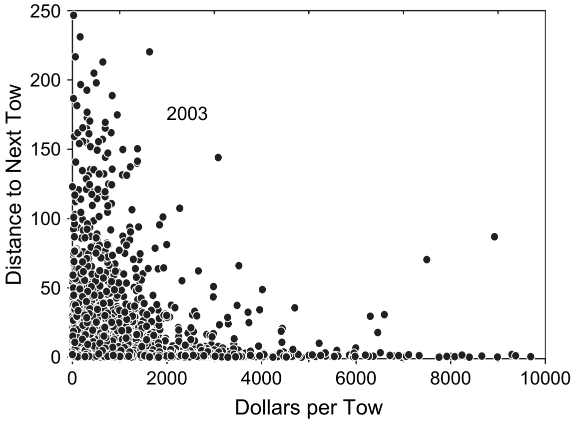

Figure 11. Relationship between total dollars generated per tow and the observed distance to the next otter trawl tow location within individual fishing trips.

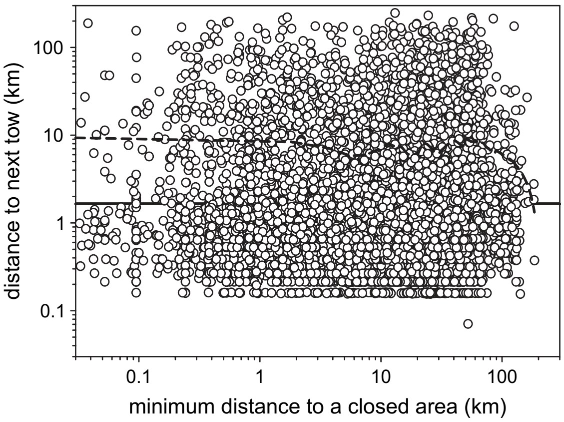

Figure 12. Relationship between minimum distance to a year-round closed area and the distance travelled to the next tow within an individual fishing trip. Linear regression and lowess smooths (10% of data) are shown.

The relationship of linear distance between sequential tows within a trip and the revenue generated on the previous tow is illustrated in Figure 11. Overall, most trawl tows occurred very close to the termination of preceding tows (nearly 50% of beginning tow locations were <1 km from the end of the previous tow). Tows producing unusually high revenues usually resulted in the next tow being made very close to the original tow location, while, conversely, many of the tows located far away from the previous tows are associated with relatively low revenues (Figure 11). These analyses suggest that scouting behaviour and risk taking in spatial decisions are infrequent, which is not surprising, given the fact that vessels are on very limited days-at-sea allocations.

Does the presence of tows near closed area boundaries influence the choice to tow in the vicinity of the last tow, or to move to a more distant location? Stated differently, is fishing effort that is deployed near a closed area boundary more likely to remain near the termination of the last tow than effort that occurs a substantial distance from the boundaries? A simple test of this hypothesis is provided in Figure 12. This analysis assesses the relationship between the distance between sequential trawl tows and the minimum distance to the five year-round closed areas. If fishers are more apt to make tows in closer proximity to each other when fishing near a closed area boundary than when fishing elsewhere, then one would expect that there would be a positive relationship between minimum distance from the boundary and the distance to the next tow. However, a log–log plot of these data reveals no discernible relationship between distance to a closed area and distance to the next tow, suggesting that fishers may not necessarily be prone to remaining at closed area boundaries if catch rates are low.

Another approach to analysing the spatial targeting behaviour between otter trawl tows involves the probability of movements of at least a given distance in relation to a number of independent variables associated with catch, economic factors, and vessel characteristics. Such approaches have been used previously to model the dynamics of spatial choice, and factors associated with movements of fishing vessels (e.g., Dorn, 1997).

One quantitative approach to assess the probability of movement is to utilize the binary logit model to categorize information of a discrete outcome (e.g. a given tow was or was not >10 km from the previous tow), with movements coded for one of two (binary) outcomes. The probability of the outcomes in relation to independent variables is:

$$y=\exp(Xb+\epsilon)/[1+\exp(Xb+\epsilon)] \quad \text{or} \quad \mathrm{logit}(y)=Xb+\epsilon \tag{2}$$

where y takes a value of 0 or 1, depending on classification of the distance response, X is a matrix of predictor scores, b the estimated effects coefficient, and ϵ is a vector of errors. Initial explanatory variables we evaluated were total revenue generated from the previous tow, the minimum proximity (distance) to a year-round closed area, the total kept catch in the previous tow, and categorical variables related to vessel size class effects (e.g. class 4 was taken as the standard, so effects were estimated for class 2 and class 3 vessels).

We chose to classify movements based on whether they were >10 km from the preceding tow or not. While most tow locations were substantially less than 10 km from the previous tow, these spatial scales were considered to be in the vicinity of the previous tow, since average tows were about 20 km in path length. Results of exploratory logit models provide insight into factors influencing spatial targeting at distances >10 km. Consistent with analyses presented in Figure 12, minimum proximity to a year-round closed area was not a significant effect (Table 5). The most consistent explanatory variable predicting distance travelled between tows was the ln of the kept catch on the previous tow, the parameter value for which was negative (implying that the probability of moving >10 km increased with low values of kept catch and vice versa). Vessel size classes were important but negative, with class 2 vessel movements significant at 5% but not 1% (Table 5). While the binary probit model correctly classified 75% of the cases by movements $>$ or ≤ 10 km, this was primarily because in 84% of cases, movements were ≤ 10 km. For movements >10 km, the correct classification percentage was only 20% (Table 5).

These exploratory analyses confirm that spatial choice was primarily influenced by catch histories and resulting revenues. There were differences among vessel size classes (generally reflecting the spatial limitations of class 2 vessels), but, in general, no readily apparent effects due to the proximity to year-round closed areas. The analyses represent an initial investigation of factors responsible for spatial choice decisions. They do not address the initial decisions of where trawl trips will allocate their first fishing effort, particularly with respect to the decision to target closed area boundaries (Figure 9). Also, they do not consider issues such as the degree of catch accumulation during the trip; trends in catch rates from within a trip, distance to/from homeport, effects of trip limits for particular species, and other issues. More detailed bio-economic modelling studies are required to examine such factors, and the degree of trip-to-trip habitual vs. profit maximizing behaviour.

Effects of seasonal closures

Seasonal closed areas to limit exploitation on spawning aggregations have a long history in the Northwest Atlantic (Halliday, 1988). In fact, closed areas I and II on Georges Bank were, in various configurations, used to protect spring-spawning components of haddock since 1970. Important questions regarding the efficacy of short-term rolling closures, however, persist (Halliday, 1988). For example, if the intent of such closures is to limit fishing mortality on animals when they are concentrated, does an influx of effort after the seasonal closure has ended negate conservation benefits accrued while the area was closed? Key issues are, then, the amount of fishing effort and associated catch rates occurring before and after the closures. Based on these considerations, previous analyses of seasonal closures to conserve haddock could not document reductions in overall fishing mortality or improved recruitment survival as a result of the seasonal closures (Halliday, 1988).

We considered patterns of fishing effort and catch rates (cpue) associated with two of the rolling closures located in the Western Gulf of Maine (Figure 13). One of the areas (RC-4&2) was closed from April to June, while the other was closed during April−May, and again during October−November. Two measures of fishing effort were derived to examine monthly patterns associated with openings and closings: the amount of effort (hours fished) in 2003 during observed otter trawl tows (Figure 5), and the amount of fishing effort documented in VMS records (Figures 4 and 13). Monthly trends in fishing effort (e.g. when each seasonal closure was open) show substantial patterns of change over the course of the year (Figure 13). In all cases, when each of the seasonal closures was opened, both VMS and observed fishing effort increased (often substantially), as compared with the amount of fishing effort exerted before the areas were closed. In particular, VMS effort (reflecting primarily class 4 vessels) increased substantially

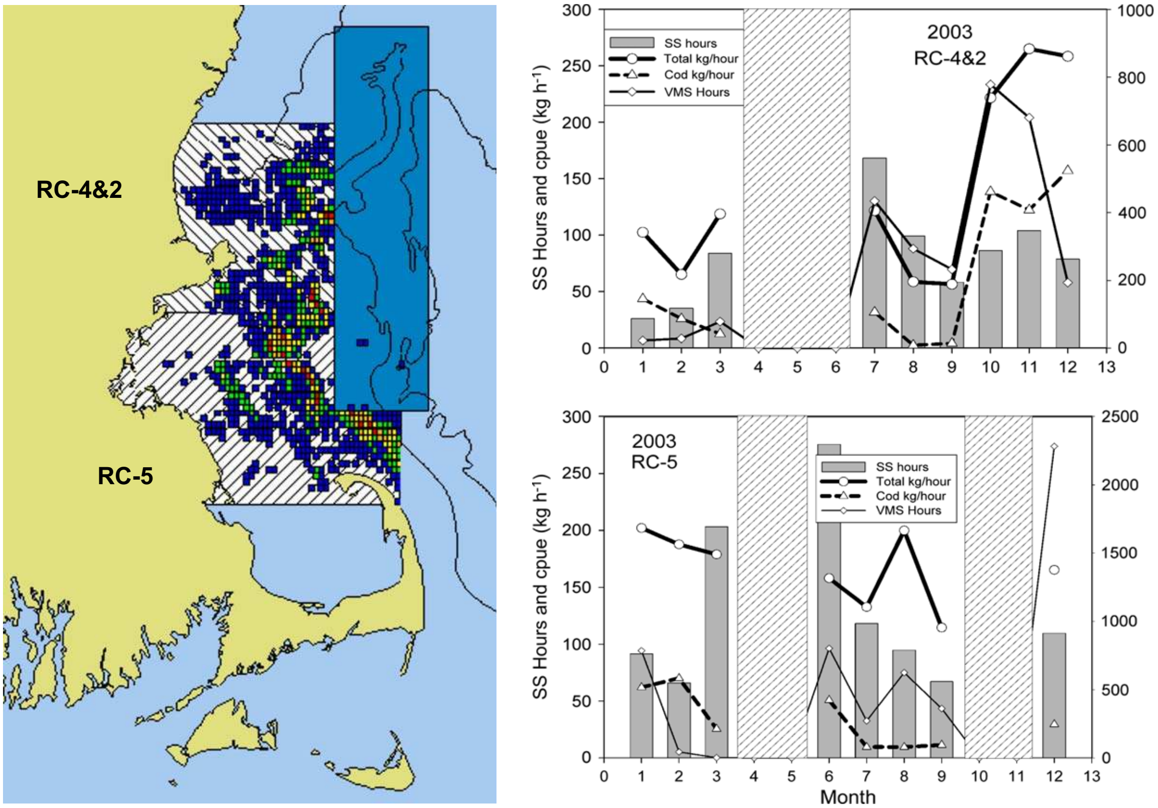

Figure 13. Monthly patterns of fishing effort and cpue associated with two seasonal closed areas off New England, 2003. Diagonal shading indicates when each area is closed to trawling. Two measures of effort are indicated [observed hours trawled (SS hours) and VMS hours]. Warmer colors (left) indicate greater amounts of VMS-derived effort.

after RC-5 opened in December, and in June. Effort apparently transferred from one of these seasonal closures to the other, given the differential patterns of openings and closings. Area RC-5 opened in June and exhibited a marked increase in effort as compared to March, the month before it closed. When RC-4&2 opened in July, effort simultaneously declined in RC-5, implying effort transfer northwards. A similar pattern occurred when RC-5 closed in October: effort increased in RC-4&2 until December. When RC-5 later re-opened, in December, there was again a corresponding effort decline in RC-4&2.

Cpue information for the two seasonal closures was derived from standardizing observer effort and catch. We plotted cpue for the all species catch rate and the catch rate for Atlantic cod (Figure 13). Cod is an important component in the nearshore Gulf of Maine groundfish fishery, and is targeted by many vessels. Cpue patterns in the seasonal closed areas change in complex ways. In all cases, cpue of all species and cod remained virtually unchanged or increased only modestly after seasonal closed areas were opened. These percentage changes in cpue were much lower than the corresponding percentage changes in effort entering the opened areas. While there may have been some initial high cpue trips just after the areas opened, when aggregated over months, no substantial “windfall” of high catch rates after the opening is evident. In some cases cpue declines occurred months after the opening, while in the case of RC-4&2 there was an increase in cpue 4 months after opening (probably the result of seasonal migratory patterns of fish).

These analyses suggest that seasonal closures in the nearshore Gulf of Maine elicit pulses of effort just after re-opening that may rapidly dissipate aggregations of fish, if these exist, and potentially undermine protection afforded to fish when the areas were closed. As effort entering the re-opened areas has to come from somewhere else, there may be corresponding declines in mortality elsewhere. Interactions between rolling closures occurs when effort is transferred from one rolling closure to an adjacent area. Overall, it is likely that potential conservation benefits to harvested stocks are somewhat dissipated due to effort influx following the opening of these areas. Given the proximity of rolling closures to year-round closed areas, there are also likely to be interactions among them, not necessarily revealed in these analyses (e.g. the pattern of rolling closures probably influences the density−distance relationships calculated in analyses described above). These analyses illustrate the complex behaviours that occur when rolling closures are employed, and emphasize the difficulty in understanding the net conservation and fishery benefits resulting from their use in fishery management.

Discussion

The implementation of year-round and rolling spatial closures off the northeast USA has fundamentally restructured the spatial dynamics of the groundfish fishery there. Effort displaced from the footprints of the year-round closures was 31% of total trawling effort, with the greatest portion of that directed to groundfish stocks. Coincident with the spatial closures, overall fishing effort was reduced to about 50% of the pre-1994 levels, so the system did not simply reabsorb displaced effort into the open areas. Interpreting changes in effort patterns around closed area boundaries is significantly confounded by changes in sampling and reporting procedures, and the spatial scales at which data are aggregated. This is because demonstrable effort attraction to the boundaries occurs at such localized spatial scales (0−5 km) that traditional 10′ square reporting is too crude to identify this pattern. Overall, it is clear that three of the year-round closures (Closed Areas I and II on Georges Bank and the Western Gulf of Maine area) attract effort to these boundaries. The Nantucket Light Ship area and the Cashes Ledge areas show no such build-up at the boundaries. Taken together, about 10% of trawling effort now occurs at distances ≤ 1 km from the year-round closures, with about 25% of effort located within 5 km.

The attraction of effort to closed area boundaries (e.g. CA-I, CA-II, and WGOM) is primarily explained by higher average $pue in the distance intervals from 0 to 4 km from the boundaries, as opposed to further away. However, while the average $pue and catch rates for some species in this distance band are about double the catch rates beyond 4 km, the variability in catch rates is significantly higher near the boundaries (Figure 9). This is likely a factor explaining why all trawling effort does not seek the closed area boundaries. Other potential factors include effort congestion at the boundaries (from both groundfish and sea scallop fishing vessels), targeting of species that do not exhibit spill-over effects, and seasonal differences in catch rates and near closures. More complex analyses of the mean-variance trade-offs in fishing strategies near the boundaries are necessary to conclude that the current distribution of fishing constitutes an optimized allocation of effort.

The higher average revenue per hour fished near some closed area boundaries is driven primarily by the apparent “spill-over” or, alternatively, by seasonal movements of a number of species, especially haddock, yellowtail flounder, and winter flounder. Some species show a neutral concentration profile with respect to distance from closed areas (e.g. cod and pollock), whereas others, particularly those occurring in deep waters, are located primarily at significant distances from the closures (e.g. monkfish, white hake, American plaice). These findings emphasize that year-round closures did not have universal positive impacts on the abundance and spill-over potential of all groundfish stocks. Rather, the critical attributes in siting the closures for conservation of a particular species are its depth distribution, degree of seasonal movement, and degree of density-driven dispersion relative to the proposed closed area boundaries. Earlier work simulating potential fishery closures on Georges Bank (Polacheck, 1990; Holland,

2000) assumed diffusion and seasonal movement of groundfish species over coarse-scale grids. Differences in diffusion potentials by species have only been revealed empirically with the adoption of closed areas and the apparent density gradients associated with them (Murawski *et al.*, 2004). It is clear that each species has a different diffusion potential with respect to the closures adopted, as evidenced by the concentration profiles (Figure 10) and the tests for spill-over (Table 4). Previous simulations did not predict nor anticipate effort concentration at fine spatial scales deployed to take advantage of near-field spill-over effects. More realistic simulation models using these finer scale data and parameters estimated from them should allow more appropriate evaluations of the conservation and economic effects of various alternative closures for the mixed-species groundfish complex.

The ability to separate true "spill-over" from directed seasonal movement patterns of species out of the closed areas is a difficult proposition, given the primary requirements for spill-over of both a density differential between open and closed areas and a density gradient within open areas. Fishery-dependent data, such as the observer data we analysed, can provide information on the latter but not the former phenomenon. Fishery-independent surveys can provide unbiased density data to assess both factors (e.g. Murawski *et al.*, 2004), but the sampling intensity of such surveys is generally limited, especially given the small spatial scales over which true spill-over apparently occurs (e.g. Figure 9). In the case of New England groundfish, density gradients estimated using fishery-dependent data indicated in most significant cases a positive relationship of density with distance, over scales of 50−∼200 km (Figure 8). These positive relationships were due to the confounding of the data with species habitat preferences and the locations of MPAs primarily in shallow waters. Thus, for relatively deep-dwelling species, the highest densities occurred at some distance from MPA boundaries. Separating the spill-over-induced density gradient from effects of environmental preferences thus represents a difficult challenge. There are a number of multivariate techniques to control for environmental preferences, including the use of generalized additive models (GAM; Goni *et al.*, 2004), and the use of multivariate regression (Murawski *et al.*, 2004). Importantly, however, we found that the spatial scale of the spill-over-induced density gradient is very localized (<4 km from MPA boundaries), as compared with the environmental gradients (depth and temperature preferences) in which the species exist. The few studies that have incorporated environmental variables in tests for spill-over have concluded that incorporation of such effects did not alter conclusions in any meaningful way, probably because of the relatively short distances over which spill-over events occurred (Goni *et al.*, 2004; Murawski *et al.*, 2004).

Exploratory analyses of spatial targeting of fishing effort revealed that cpue and $pue are the most influential determinants of the locations of sequential trawl tows within a fishing trip. The proximity to year-round closures had negligible influence on these choices, but these analyses did not account for initial choices of fishing locations (e.g. to start a trip adjacent to a closed area). More complex models of spatial behaviour are necessary to discern what determines initial targeting choices. These should link sequential trips looking back over several fishing seasons to discern habitual vs. profits-maximizing behaviours in targeting decisions. Other potential explanatory variables for tow-by-tow allocation could be explored including the first differences in catch rates (e.g. is the trends in cpue, the degree of vessel "loading" due to cumulative catch onboard, and the tendency to "top off" trips as the vessel is steaming to port). Overall, movements between tows >10 km were rare, reflecting the fact that the days-at-sea limitations in effect in this fishery are not conducive to scouting behaviour or substantial risk-taking in spatial choice dynamics of where to fish.

Previous studies of spatial choice dynamics for mixed-species groundfish fisheries (Holland and Sutinen, 1999, 2000; Hutton *et al.*, 2004) used random utility theory or simulations to predict effort allocation among large-scale statistical reporting areas, on a trip-to-trip or coarser temporal basis. Explanatory variables determining location choice were lagged catch rates and the value of catches (Holland and Sutinen, 1999; Hutton *et al.*, 2004) and habitual patterns of effort allocation (Holland and Sutinen, 2000). These previous studies used self-reported logbooks to deduce gross allocation behaviours. However, there may be substantial problems in deducing allocation behaviours from these data. Aggregating many individual tows into a trip record may reduce highly variable fishing locations to a single position or statistical grid because of reluctance to provide exact locations associated with fishing success. Additionally, there is the potential for other reporting biases in these data affecting the estimates of catches, revenues, changes in target species choices within a trip, and other variables. Our analyses were based on information independently collected by scientific observers aboard vessels. They include careful measurements of both the kept and discarded portions of the catch, and precise locations of the start and end points of each tow. With the use of observer data, analyses of spatial allocation behaviour can incorporate much finer resolution, thus allowing interpretation of location choices appropriate to the time and space resolution associated with MPAs and seasonal closures. The challenge will be to integrate observer records, which may not include sequential trips on the same vessel, with VMS or other precise vessel locations (on observed and non-observed trips), and traditional logbook data into a modelling framework describing spatial choice dynamics at scales appropriate to various management questions.

Rolling (seasonal) closures attracted effort into the areas once they are re-opened (Figure 13). In some cases these increases in effort were associated with higher monthly cpue, but in other cases, not. The presence of multiple adjacent rolling closures operating out of phase displaces effort among the areas, depending on which one is opening or closing. Overall, it is likely that conservation benefits accruing from the use of rolling closures may be undermined by the pulses of effort once the seasonal closures are re-opened.

These analyses confirm that large-scale year-round closed areas, in effect now for more than a decade, affect the abundance and spatial distribution of some target species, and the allocation of trawling effort. The year-round closures have generated build-up of some, but not most, of the groundfish stocks within the boundaries of the closed areas. Apparent spill-over of animals outside of the year-round closed areas is driven by a few valuable species, and this differentially attracts some effort to the boundaries of three of the five closures.

Acknowledgements

Information upon which this paper is based was collected through the combined efforts of the Northeast Fisheries Science Center's Observer Program (sea sample data), the Regional Enforcement Program (VMS data), and the Regional Statistics program (vessel trip reports). We appreciate the continued dedication of individuals and groups committed to assuring accurate and timely data, and innovative systems for accessing them. Chad Keith helped in developing GIS coverages and analyses for these data. Finally, we appreciate the thorough and helpful reviews of the manuscript supplied by Fred Serchuk, Jeremy Collie, and Stuart Rogers.

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