FISH and FISHERIES

Empirical move-on rules to inform fishing strategies: a New England case study

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Abstract

Increasingly, fisheries are being managed under catch quotas that are often further allocated to specific permit holders or sectors. At the same time, serious consideration is being given to the effects of discards on the health of target and non-target species. Some quota systems have incorporated discard reduction as an objective by counting discards (including unmarketable fish) against the overall quota. The potential effect of the introduction of a quota system that includes accountability for discards on the fishing strategies employed by fishermen is enormous. This is particularly true for multispecies fisheries where healthy and depleted stocks co-exist; resulting in a trip's catch being applied to very large and very small stock quotas simultaneously. Under such a scenario, fishermen have a strong incentive to minimize (i) catch of low-quota or 'choke' stocks, (ii) regulatory discards due to minimum size limits and (iii) catch partially consumed by predators. 'Move-on' rules (i.e. event-triggered, targeted, temporary closure of part of a fishery when a catch or bycatch threshold is reached) have been employed in a variety of fisheries. However, their efficacy has been limited by a lack of empirical analyses underpinning the rules. Here, we examine the utility of spatiotemporal autocorrelation analyses to inform 'move-on' rules to assist a sector of the New England Multispecies Fishery to reduce discards and maximize profits. We find the use of empirical move-on rules could reduce catch of juvenile and choke stocks between 27 and 33%, and depredation events between 41 and 54%.

Keywords Choke species, discards, move-on rules, New England multispecies fishery, real-time closures, spatiotemporal autocorrelation

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Introduction

The influence of sector-based management on fishing strategies in New England

The productivity of waters and fisheries off the coast of New England has been widely recognized (McFarland 1911; Kurlansky 1997; Rosenberg *et al.* 2005; Alexander *et al.* 2009). The historic economic importance of the Atlantic cod (*Gadus morhua*, Gadidae) fishery to the development and economy of the region cannot be overstated (Ackerman 1941; Innis 1954; Doeringer *et al.* 1986). However, persistent growth and recruitment overfishing leading to sequential depletion of stocks has resulted in trophic cascades and a fundamentally altered ecosystem (Murawski *et al.* 1997; Fogarty and Murawski 1998; NEFSC 2012; for regional examples, see also Myers and Worm 2003; Frank *et al.* 2005). Although some successes at rebuilding stocks have been noted, the latest stock assessment update listed 80% stocks in the Northeast Multispecies Fishery Management Plan (FMP) as being overfished and/or experiencing overfishing (NEFSC 2012). Recent amendments to the FMP have sought to address these problems through a sweeping restructuring of the fishery. The main change was the introduction of a hard quota and catch shares, which have been shown to halt or reverse fishery collapses (Costello *et al.* 2008). Amendment 16 both expanded the scope of the FMP and allocated quota for 16 groundfish stocks between sectors and a common pool, and ushered in accountability for both landings and discards for the first time (NMFS 2010). Sector management, whereby fishermen voluntarily formed groups (or 'sectors') with pooled allocations based on their historical fishing and managed primarily under a quota, offered an appealing alternative to the 'common pool' which retained input controls such as days-at-sea and trip limits. Fishermen overwhelmingly chose to join sectors: 95% of the historical landings in the multispecies groundfish fishery participated in sectors in FY 2010 (NEFSC 2012).

The potential effects of the new quota system and accountability for discards on the fishing strategies of New England fishermen are enormous. The nature of multispecies fisheries like the New England groundfish fishery is such that healthy and depleted stocks co-exist, which can result in the catch of stocks with very large and very small quotas simultaneously. The smallest allocations are often referred to colloquially as 'choke stocks' because once filled they choke off access to other stocks in that area (or require the fishermen to lease more quota). As the amount of quota held by a fisherman or a sector varies widely, what is considered a choke stock differs among individuals, between individuals and sectors, and among sectors.

Beyond the low-quota 'choke' stocks, discards represent another potential cost to fishermen's profitability. Here we define discards as fish that cannot be landed due to regulatory or market constraints and therefore generate no profit, whereas landings are fish that are landed and sold. After the passing of Amendment 16, minimum size limit regulations are the only allowable regulatory discard in the FMP. Catch of any 'allocated' species, including such juvenile discards, are now counted against the sector's quota. Thus, juvenile catch and market discards (e.g. any fish that is unmarketable due to depredation by sharks, rotting, gear damage, etc.) now have a double cost, as the fishermen are unable to reap a profit from the catch and it also counts against the sector's quota.

Previously, fishermen in the New England multispecies groundfish fishery sought to land enough of a target stock to fill multiple stock-specific trip limits, while minimizing the operational costs of running a fishing vessel (crew, bait, fuel, etc.). With the implementation of Amendment 16, this equation has fundamentally changed. Landings are no longer constrained by trip limits and as such the incentive to maximize catch of target stocks has increased. However, fishermen now must also factor the cost of leasing more quota and lost quota due to discards into their fishing strategy. Consequently, sector members have a strong incentive to minimize (i) the catch of choke stocks, (ii) regulatory discards largely due to minimum size limits and (iii) depredation events. The use of market measures to enable catch-quota balancing in multispecies fisheries has been well discussed in the economics and policy literature (Buck 1995; Squires *et al.* 1998; Dupont and Grafton 2000; Sanchirico *et al.* 2006). Work has also been done to examine how fishermen shift effort allocation to target specific mixes of stocks when transferable quota systems are implemented and fishing strategies are altered (Branch and Hilborn 2008; Poos *et al.* 2010). However, little work has been done to consider what information might be useful to fishermen to inform their allocation of fishing effort under the new incentive structure. Here, through a cooperative research approach including fisheries biologists, spatial ecologists, sector managers and fishermen, we examine the utility of spatiotemporal autocorrelation analyses to inform 'move-on' guidelines to assist a sector to reduce discards and maximize their profit.

We define a move-on rule (also known as 'encounter protocols') as a regulation or guideline that triggers the targeted closure of an area in a fishery to one or more gears for a temporary period when a catch (or bycatch) threshold is reached, without closing the entire fishery. Specifically, such move-on rules provide a distance that fishermen should move, or the amount of time they should wait, to avoid a certain type of catch. They are commonly implemented to reduce catch of juveniles or non-target species. We differentiate such rules from general event-triggered closures, which are most often applied to a whole fishery and remain in place until the following season (e.g. the closure of a fishery when a bycatch quota is reached). Similarly, they also differ from time–area closures, as time–area closures are generally not dynamically instantiated (i.e. based on the occurrence of a particular event).

Spatiotemporal autocorrelation in fisheries

Dunn *et al.* (2011) offer a framework for minimizing discards and increasing catch selectivity through the use of spatiotemporal management measures (i.e. time–area closures). The authors put four types of analytical methods (periodicity, local indicators of spatial association, space–time autocorrelation, and oceanographic correlate analyses) in a decision tree where each node adds management complexity, but also decreases the time/area affected. The first two groups of methods can inform seasonal and time/area closures. Seasonal closures and time/area closures have been extensively used to, among other objectives, mitigate bycatch (Dawson and Slooten 1993; Witherell and Pautzke 1997; Murray *et al.* 2000; Hooker and Gerber 2004; Notarbartolo di Sciara *et al.* 2008; PFMC 2008; AFMA 2009a,b). However, Dunn *et al.* suggest that when the goal is to decrease bycatch or discards, these types of closures may be less useful than other types of closures and are likely to result in coarsely targeted management measures. Alternatively, the authors indicate that consideration should be given to event-triggered closures or dynamic oceanography-based closures that can more efficiently meet the bycatch or discard mitigation objective (i.e. do so while minimizing lost target fish catch and economic burden for fishermen). Dynamic empirical oceanographic closures have recently been employed in Hawaii and Australia to mitigate bycatch (Hobday and Hartmann 2006; Howell *et al.* 2008; Hobday *et al.* 2010) and the scientific literature contains many examples of how oceanographic habitat models can be used to implement such closures (Hyrenbach *et al.* 2006; Palacios *et al.* 2006; Eckert *et al.* 2008; Block *et al.* 2011; Louzao *et al.* 2011; Nur *et al.* 2011; Zydelis *et al.* 2011). Although move-on rules have been around longer than oceanographic closures (Kenchington 2011), they have received far less attention in peer-reviewed literature.

Move-on rules in fisheries management

Move-on rules have been incorporated to varying degrees in the management of a number of fisheries (Table 1). These measures have been utilized from Antarctica to Norway, and in fisheries employing everything from anchored gillnets to pelagic longlines to purse seines. Generally speaking, they are most frequently implemented to reduce bycatch of juveniles or non-target species (including finfish, protected species and corals or sponges). Kenchington (2011) and Shotton and Patchell (2008) offer non-exhaustive reviews of the use of move-on rules in the context of the development of encounter pro-

Table 1 Examples of the range in type and geographic scope of fisheries that utilize move-on rules. The literature describing these examples provides little to no explanation for the times and distances employed. Distances are given by either straight nautical mile (nmi) distance from a set or as an area (in nmi^2) around the set.

Management measure	Fishery	Country	Move-on distance	Move-on time	Frequency of assessment	Threshold (trigger mechanism)
Chinook Salmon Bycatch Reduction Plan and Agreement (i.e. the Voluntary Rolling Hotspot System; Madsen and Haflinger 2010)	Walleye Pollock Bering Sea and Aleutian Island Fishery	USA	Expert opinion	7+ days, based on vessel bycatch rate	Weekly	Based on an analysis of areas that exceed the base bycatch rate (a moving average)
Scottish Cod Conservation Credits (Holmes *et al.* 2011; Needle and Catarino 2011)	Mixed gear, demersal whitefish fishery (targeting cod, haddock and whiting)	Scotland	50–225 nmi^2	21 days	Daily	Triggered when catch rates exceed 40 juvenile cod per hour of fishing
Cod juvenile and spawning real-time closures (MMO 2012)	North Sea and Skagerrak fisheries using particular gears	EU and Norway	23 or 64 nmi^2, depending on distance from shore	14 days, 21 days or a calendar month, depending on distance from shore	Daily for at-sea inspections or voluntary notification by fishermen; also have monthly for LPUE-based closures	Triggered when catch of mature cod (>50 cm) exceeds 10 per hour of fishing, or 80 cod (all sizes) per hour of fishing
Juvenile real-time closures (European Commission 2011)	North Sea and Skagerrak fisheries using particular gears	EU and Norway	50 nmi^2	21 days	Theoretically upon encounter, but based on country reporting to the EU.	Triggered when catch rates of juveniles exceed 7.5% or 10%, depending on the overall ratio of cod in the catch.

Table 1 Continued.

Management measure	Fishery	Country	Move-on distance	Move-on time	Frequency of assessment	Threshold (trigger mechanism)
Conservation Measures 33, 41 & 42 (CCAMLR 2011)	Patagonian toothfish and mackerel icefish fisheries. Some measures affect other Antarctic fisheries	CCAMLR	5 nmi	5 days	Real time (upon encounter)	Various. Used to limit juvenile mackerel icefish catch and bycatch of non-target species in specific statistical areas
Vulnerable Marine Ecosystem Encounter Protocols (Auster *et al.* 2010)	Deep-sea fisheries in areas beyond national jurisdiction	Various RFMOs	Generally, 1–2 nmi^2	Generally, until review	Real time (upon encounter)	Implementation of the protocols is highly variable between the various RFMOs
Gulf of St. Lawrence groundfish small and incidental catch protocols (DFO 2008)	Atlantic groundfish fisheries	Canada	Management area	>10 days, based on catches from a test fishery	Daily, based on at-sea-observer reporting	Triggered when catch of ‘undersized fish reaches or exceeds 15% of the catch of any of the species [with a minimum size limit] or when incidental catches of a closed species reaches or exceeds the established level for the fleet’
Gulf of St. Lawrence herring fishery small fish protocols (DFO 2009)	Atlantic herring fisheries	Canada	Expert opinion	>5 days, based on catches from a test fishery	Daily, based on dock-side monitoring	Triggered when catch of juvenile herring ‘exceeds 25% of the total number of herring that were caught and retained during that fishing trip…’

Table 1 Continued.

Management measure	Fishery	Country	Move-on distance	Move-on time	Frequency of assessment	Threshold (trigger mechanism)
Coral/sponge encounter protocols (DFO 2011)	British Columbia groundfish trawl fishery	Canada	Vessels will be encouraged to avoid the area where the bycatch of coral and sponge occurred	Vessels will be encouraged to avoid the area where the bycatch of coral and sponge occurred	Daily, based on at-sea-observer reporting	This procedure will be followed any time a vessel catches more than 20 kilograms of combined corals or sponges in one tow
Hoki small fish move-on rule (Shotton and Patchell 2008)	Hoki fishery	New Zealand Hoki Fishery Company (New Zealand)	5 nmi	5 days	Real time (upon encounter)	Move-on rule was implemented if 10% of catch (by numbers) were juvenile hoki
Fish aggregating device (FAD) closures (WCPFC 2009)	Purse seine fishery for highly migratory fish stocks	Western and Central Pacific Fisheries Commission	50 nmi	7 days	Upon retrieval of a FAD	Applies to fishing after retrieval of a FAD during a FAD closure
Right Whale Dynamic Area Management (DAM; NMFS 2002)	Lobster trap/pot and gillnet	USA	15 nmi around a “core area”, defined by a polygon encompassing the 15 nm buffer zone	15 days	Daily, but not applied until ‘2 days after publication of a notice in the Federal Register’	A DAM zone will be triggered by a single reliable report from a qualified individual of 3 or more right whales within an area (75 nm^2; 139 km^2) such that right whale density is equal to or >0.04 right whales per nm^2 (1.85 km^2)

tocols for deep-sea fisheries in response to United Nations General Assembly Resolution 61/105 which called for Regional Fisheries Management Organizations (RFMOs) to prevent Significant Adverse Impacts to Vulnerable Marine Ecosystems.

While move-on rules are being used, there are no examples of an empirical approach to determining the times or distances employed. That is, each example appears to have been formulated either by expert opinion or through negotiation with stakeholders. Although analyses of the underlying spatiotemporal autocorrelation or patch dynamics in the catch data could inform the choice of times and distances employed in move-on rules, we could find no rules generated by such analyses. The origin of existing rules is almost never clear, but some appear to have been generated by simply assimilating values used in other fisheries (e.g. the CCAMLR examples), or by increasing times or distances when stocks become overfished (e.g. the New Zealand hoki example). Some rules offer no guidance on the time or distance to be moved at all (e.g. the BC groundfish example), while others rely on expert opinion to draw a polygon around hauls with high bycatch rates (e.g. the Bering Sea and Aleutian Islands (BSAI) pollock fishery). Examples like that seen in the BSAI pollock fishery may actually be considered more of a time/area closure, as they do not offer guidance in response to a single event (or encounter), but use a group of events to define an area to be closed.

Here we develop data-driven move-on guidelines to assist the efficient utilization of multiple quotas. These rules can inform on-the-water decisions by fishermen and enable real-time management of fisheries by providing information on the extent and persistence of negative catch events (i.e. catch of choke species and juveniles or depredation events). We believe that as these guidelines are implemented, they will be the first move-on rules utilizing empirically based times and distances employed by a fishing industry. Further, we have implemented these analytical approaches in freely available software tools so that other sectors and fisheries may apply these methods.

Methods

A collaborative approach

This study was a collaboration between the Cape Cod Commercial Hook Fishermen's Association (CCCHFA), the Georges Bank Cod Fixed Gear Sector and the Marine Geospatial Ecology Laboratory (MGEL) at Duke University. CCCHFA is a non-profit organization that actively campaigns for a healthy marine environment to support a secure and viable future for sustainable commercial fisheries. The GB Cod Fixed Gear Sector is an organization of commercial fishermen who have come together to collectively manage annual allocations of fish under the Northeast Multispecies FMP. Through a series of meetings in Chatham, Massachusetts, fishermen, sector managers, fishery biologists, spatial ecologists and tool developers sat down to describe fishing activities, outline the problem space, generate research questions, present methods, and vet final results. The Maine Coast Fishermen's Association and the Port Clyde Community Groundfish Sector also participated in these meetings. This type of collaboration, and the actionable results derived from it, was only possible through the work of the sector manager (a co-author, EB) and the CCCHFA to bridge the gap between scientists and fishermen, and to generate the level of trust required in such a project.

Data

We examined spatiotemporal distribution of catch and discard data using observer data produced by the Northeast Fisheries Observer Program (NEFOP). NEFOP is a program of the Northeast Fisheries Science Center (NEFSC) of the National Marine Fisheries Service (NMFS), and collects, maintains and distributes data for scientific and management purposes in the northwest Atlantic Ocean. After initial meetings describing the project to the fishermen, data waivers for 36 vessels were obtained by the authors associated with the GB Cod Fixed Gear Sector (EB, MS), affording access to high-resolution fishing effort and catch data necessary to perform the analyses. Although Fixed Gear Sector fishermen employ handlines, benthic longlines and anchored sink gillnets (both large mesh and extra-large mesh), due to limited sample sizes, only data pertaining to gillnet sets were used. The observer data spanned 6 years (2005–10) and contained information on 1110 gillnet hauls, including 9343 catch records (i.e. species by haul and disposition of the catch). Records with no catch or no information on species, location or mesh size were removed. As different species are targeted with different mesh sizes (per

National Marine Fisheries Service regulations), we further divided the gillnet sets into two categories: large mesh (<8 inches; $n = 455$ sets) and extra-large mesh (≥ 8 inches; $n = 541$ sets). We focus this analysis on the large-mesh stand-up gillnets that are primarily used to target Atlantic cod and pollock (*Pollachius virens*). Any large-mesh gillnet sets employing tie-downs (i.e. a line used to connect the bottom of a gill net to the top, to create a bend or pocket in the net) were discarded ($n = 22$), as they were used to target other species.

The Space–time *K* function

Data on catch positions may be thought of as a marked point process (Stoyan 1984a,b; Baddeley 2008). While typical analyses of spatial point processes are evaluated against a null hypothesis of Complete Spatial Randomness, marked point processes consider the distribution of marks compared to an underlying distribution of events to which they belong. For example, from the perspective of this study, we test whether the distribution of gillnet hauls containing catch depredated by hagfish is clustered or over-dispersed in comparison with all gillnet haul positions. The spatial and temporal scales over which the pattern occurs can inform management by indicating the distance in space and time a fisherman must move his/her gear (or wait) to reach an area where the marked point process (e.g. hagfish depredation) no longer exhibits autocorrelation. In this study, we are specifically interested in clustering, as the aggregation of events over small distances and short timeframes presents an opportunity for the targeted use of event-triggered closures to avoid such cases.

We follow the methods presented in Gardner *et al.* (2008) but, given our specific interest in informing move-on rules, focus our attention on clustering in space–time interactions. Here we summarize those methods and concentrate on the specifics of our approach. To analyse spatial and temporal autocorrelation in the marked point processes, we applied a variation on Ripley's *K* function (Ripley 1977). Ripley's *K* compares the expected intensity of events (i.e. fishing sets) based on a global mean from the entire data set, to the intensity found in the marks (i.e. hauls with catch of choke stocks, regulatory discards or depredation events). The space–time *K* function can be described by the equation

$$\hat{K}(d,t) = \frac{AT}{N^2}\sum_{i=1}^{N}\sum_{j\neq i}^{N}\frac{I(||s_i - s_j|| \leq d)I(||h_i - h_j|| \leq t)}{w(s_i,s_j)v(h_i,h_j)},$$

for $t,d > 0$ (Diggle *et al.* 1995; Gatrell *et al.* 1996; Gardner *et al.* 2008). N is the total number of events, A is the total area, T is the total length of the time series (in days), s_i is the spatial location of event i and h_i is the time of event i. The weight $w(s_i,s_j)v(h_i,h_j)$ is an edge-correction factor equal to the proportion of the circle centred at s_i that is inside the study area and the proportion of the time interval centred at h_i that is inside the observed time span. The indicator function I() identifies those events s_j,h_j that are within a distance d and time t of the event s_i,h_i. As we are comparing the distribution of marks with the overall distribution of events, the overall distribution is subtracted from the initial *K* function. This function can also be linearized (Besag 1977) and scaled to aid interpretation

$$\hat{L}_m(d,t) = \left(\sqrt{\hat{K}_m(d,t)/\pi} - \sqrt{\hat{K}(d,t)/\pi}\right)/\max t,$$

To eliminate purely spatial effects (e.g. depth gradients) and temporal effects (e.g. seasonal fluxes in water temperature), we subtract the independent space and time autocorrelation

$$\hat{D}_m(d,t) = \hat{L}_m(d,t) - \hat{L}_m(d)\hat{L}_m(t),$$

In doing so, we isolate the effect of only those processes that are correlated in both space and time. We test the null hypothesis that the spatio-temporal autocorrelation in the marks is not significantly different than exhibited by all fishing sets. We use random labelling, a permutation test where points within the overall fisheries data set are randomly labelled as marks, and compare the distribution of results from the permuted events to those found using the true marks (Kenkel 1988; Cuzick and Edwards 1990). We ran one thousand permutations and calculated a test of statistical significance by comparing the overall sum of $\hat{D}_m(d,t)$ across all d and t with the frequency distribution of the sums of each, for $i = 1$–1000. As we considered only clustering, we used a one-sided test and considered values of $\hat{D}_m(d,t)$ above the 95% of the distribution of permuted values ($\alpha = 0.05$) to reject the null hypothesis of no difference in clustering between the marks and the overall data set (Diggle *et al.* 1995; Loosmore and Ford 2006).

Further, to find the scales of the spatiotemporal autocorrelation, we plotted $\hat{D}_m(d,t)$ against the 95% envelope of the permuted values. Values above the envelope indicate spatial clustering is present. However, as all points within a given distance are used to calculate the K function, $\hat{D}$ values are correlated to those values at shorter distances. While there are drawbacks to this method of calculating autocorrelation (Wiegand and Moloney 2004; Lewison *et al.* 2009), it is useful for finding threshold distances; the distance up to which the marks are more clustered than the overall data set. Such thresholds are indicated by peaks in the surface of $\hat{D}_m(d,t)$; however, these values above the envelope do not infer statistical significance at each separate d and t. For ease of visualization, the 95% envelope is subtracted from $\hat{D}_m(d,t)$, and we normalize the values between 0 and 1 in our figures. Thus, any values >0 indicate a response outside the 95% envelope and those values of 0 show no difference from random. Peaks in spatiotemporal autocorrelation are indicated by a value of 1. All analyses were carried out using the software program R (R Core Team 2012) and the splancs package (Rowlingson and Diggle 1993).

We applied the spatiotemporal K function to four types of events: catch of choke and nuisance stocks, catch of juveniles, and depredation events (Table 1). After discussion with fishermen, it was suggested that yellowtail flounder (*Limanda ferruginea)* be considered a choke stock. Fishermen and the sector manager were also concerned with avoiding barndoor skate (Dipturus laevis), but for slightly different reasons. They suggested barndoor skate could reach such high densities in a given area that it reduced CPUE of target stocks thereby forcing the fishermen to move gear to new fishing grounds (E. Brazer, personal communication). As it is not lack of quota, but hyper-aggregation of a non-target species that prevents fishing in the area, we differentiate barndoor skate from yellowtail flounder and refer to it as a nuisance stock. While we did not consider cod a choke stock in this study, the most recent stock assessment for Gulf of Maine cod reversed previous findings of improvements in the fishery and recommended major reductions in the GOM cod quota (NEFSC 2012). Given the likely cuts to the GOM cod quota based on the stock assessment, the stock will become a choke stock for GB Cod Fixed Gear Sector fishermen targeting GOM haddock (and any other sectors active in the region). Juvenile catch of target species (cod and pollock) was also investigated. Lastly, we looked at depredation events. There are four main sources of depredation events in the fishery: sharks (generally, spiny dogfish *Squalus acanthias*), gray seals (*Halichoerus grypus*), Atlantic hagfish (*Myxine glutinosa*) and ‘fleas’ (marine amphipods). Depredation by sharks, hagfish and fleas was included in the analysis but, due to a lack of data, depredation by gray seals was not.

We initially limited our analysis of spatiotemporal clustering in catch events to 10 km and 30 days, acknowledging that move-on rules beyond these extents would be economically infeasible. However, to insure that the maxima visible within the extents of the initial study were not local maxima, we repeated the analysis over 50 km. Proposed move-on distances (in time and space) were derived from peaks in the $\hat{D}_m(d,t)$ surface (i.e. the distance and time-lag to the peak). To test the efficacy of the proposed move-on distances, we implemented a script to iteratively run through the marked hauls by date and time and remove any future hauls within the time and distance specified by the move-on rule. The hauls that were ‘removed’ from the data set during further iterations represent fishing activities that would have been performed in a different location (or not at all). The number of marked hauls (i.e. those associated with one of the event types considered) and the number of unmarked hauls (i.e. those not associated with the event considered) ‘removed’ were compared to the total number of marked hauls and unmarked hauls to derive event rates inside and outside of the extent of the move-on rule.

Results

All catch types displayed overall spatiotemporal patterns over 10 km and 30 days, significant at $P < 0.05$, except catch of barndoor skate (Table 2). Space–time interactions were apparent in the surfaces for each event type considered, including barndoor skate. Both yellowtail flounder and barndoor skate exhibited autocorrelation (Fig. 1a & b). While spatiotemporal autocorrelation in barndoor skate catch was not significant over 10 km and 30 days, space–time interaction was still visible at short distances and time lags (2 km and 2 days). Given the clear and strong

Table 2 Significance test for overall spatiotemporal clustering, move-on distances and performance measures for choke stocks, juvenile catch and depredation events. The sum of is compared to the 95% quantile of 1000 random labelling permutations of the spatiotemporal *K* function.

Group	Species	95% random labelling quantile ($\times10^{15}$)	Sum of D-hat in marks ($\times10^{15}$)	Move-on distance (km)	Move-on time (days)	n_{marks}	Marked hauls within move-on rule (%)	Unmarked hauls within move-on rule	Rate of marked hauls within move-on rule (%)	Rate of marked hauls outside move-on rule (%)
Choke	Yellowtail Flounder	7.884	13.249*	6.5	1	31	10 (32.3%)	19 (4.7%)	34.5	5.2
Nuisance	Barndoor Skate	9.894	9.149	2	2	20	4 (20.0%)	22 (5.3%)	15.4	3.9
Juvenile	Cod	5.059	7.233*	2.5	1	163	84 (51.5%)	37 (13.7%)	69.4	20.0
Juvenile	Pollock	6.119	8.935*	3.5	1	62	27 (43.5%)	41 (11.1%)	39.7	8.9
Depredation	Fleas	6.409	13.186*	2	2	59	27 (45.8%)	3 (0.8%)	90.0	7.4
Depredation	Hagfish	6.109	13.978*	3	5	69	42 (60.9%)	22 (6.0%)	65.6	7.1
Depredation	Shark	10.594	33.035*	6	1	19	9 (47.4%)	6 (1.4%)	60.0	2.3

$^*P < 0.05$.

peak at a short distance, we re-ran the spatiotemporal *K* function limited to 5 km and 30 days. The sum of the values was significant at this shorter distance.

Catch of juveniles also exhibited space–time interaction across both species considered (Fig. 1c & d). Juvenile cod and pollock catch demonstrated very clear trends and both had thresholds at very short times and distances (2.5–3.5 km and 1 day). Trends in time were also clear in depredation events although identification of threshold values was slightly more difficult due to indistinct trends over distance (Fig. 2). Although flea damage and hagfish damage continued to exhibit local peaks in spatiotemporal autocorrelation out to ~14 km, much of that autocorrelation is due to autocorrelation found at shorter distances (i.e. the distances examined in our study). As such, we are confident that our results (2 km and 2 days for flea-damaged catch, and 3 km and 5 days for hagfish depredation) represent operable thresholds. Shark damage exhibited an oddly even trend in space and time, likely due to a small sample size (n = 19 shark depredation events). It did, however, have a specific peak at 6 km and 1 day.

Analysis of the efficacy of the proposed move-on guidelines offered strong evidence for the utility of move-on rules and the validity of the approach taken in this study (Table 2). An ideal move-on rule would encompass all negative catch events within it limits and as few events without negative catch as possible. The best results were clearly the move-on rules for depredation events. If the recommended move-on rule had been in place, the rate of depredated hauls (depredated hauls/all hauls) would have declined by nearly half (47.1%; SD = 0.063), while only a small fraction (2.8%) of the non-depredated haul would have been affected. The rate of depredated hauls within the move-on rules was a factor of 9.3–25.6 times the rate of depredated hauls outside the move-on rules. The move-on rule for juvenile catch was similarly effective, reducing the juvenile haul rate (hauls with juveniles/all hauls) over 30% (32.9%; SD = 0.002). However, on average, 12.4% of hauls with no juvenile catch were affected, resulting in the juvenile haul rate outside the move-on rule being only 3.5–4.5 times higher than the rate inside the bounds of the move-on rule. Choke and nuisance stock catch was the least mitigated by the move-on

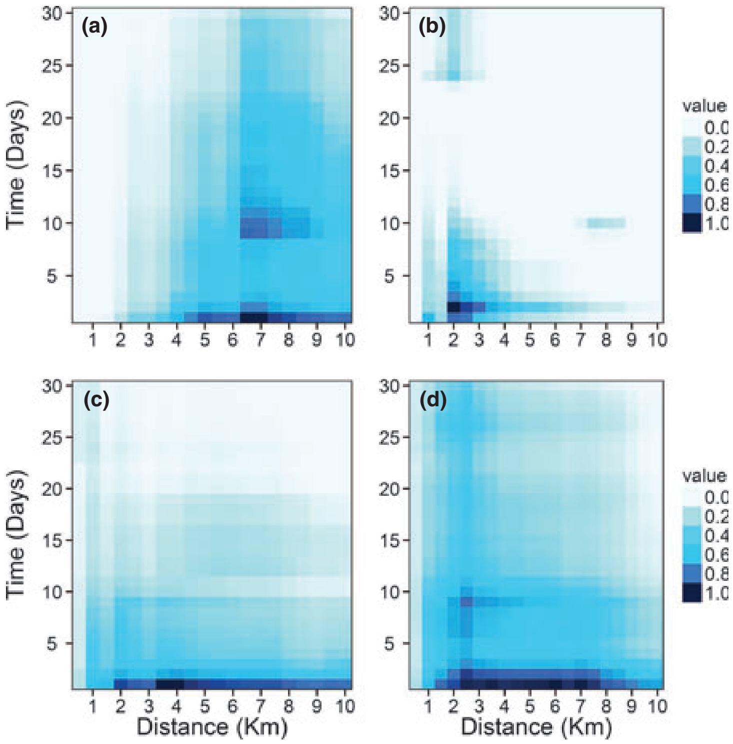

Figure 1 Spatiotemporal autocorrelation in catch of (a) yellowtail flounder and (b) barndoor skate stocks, and juvenile catches of (c) cod and (d) pollock for large-mesh stand-up gillnet gear. Colour values are unitless and represent relative distance above the 95% envelope generated from 1000 random label permutations. Peaks in the surface indicate the spatiotemporal extent of the clustering. That is, a value of one corresponds to the highest autocorrelation value within over the time and distances used in the analysis.

rule, the rate of hauls with these stocks (hauls with choke or nuisance stocks/all hauls) would have been reduced 21.1% (SD = 0.088), but would have affected only 5.0% of the non-choke or nuisance stock hauls. As such, the difference in the rate within the move-on rule was slightly higher than that found for the juvenile catch move-on rule (4.0–6.6 times the rate outside the extents of the move-on).

Discussion

Our analyses revealed strong space—time interactions in virtually all of the most important catch types related to the use of quota in the multispecies groundfish fishery in New England. Catch of choke and nuisance stocks, catch of juveniles, and depredated catch all exhibited peaks in spatiotemporal autocorrelation that can inform move-on rules empirically. Most of the threshold values derived from our analyses are at distances under 4 km and at time lags of 2 days or less. Several fall within 2 km and 2 days. These are actionable and operable scales for groundfish fishermen, and adherence to the move-on rules may be less economically detrimental than continued fishing in an area with a higher likelihood of negative catch events. While no attempt was made to determine the ecological underpinning for the move-on times and distances, we suspect they are related to movement behaviour of the stocks as well as the persistence of ephemeral oceanographic conditions.

The results of the validation exercise provide strong support for the use of move-on rules to avoid catch of choke and nuisance stocks, juveniles, and particularly in avoiding depredation events. An astounding 90% of hauls within the range of the move-on rule for flea depredation were flea-damaged hauls. This figure is all the more dramatic given that the extent of the move-on rule was just 2 km for 2 days. Further, only 0.8% of all unmarked sets were affected by the rule (i.e. 0.8% of all sets without flea damage would have been re-located to a different area). This efficiency was matched by the effectiveness of

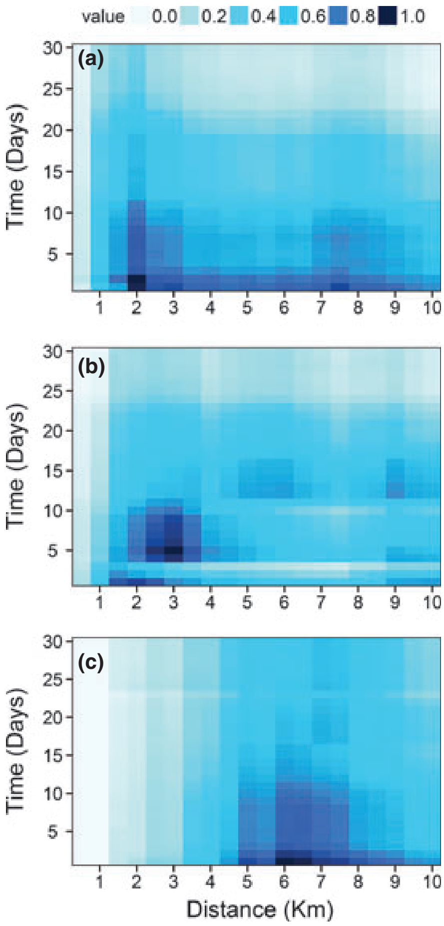

Figure 2 Spatiotemporal autocorrelation in depredation events in sets using large-mesh stand-up gillnet gear: (a) depredation by fleas, (b) depredation by hagfish, (c) depredation by sharks. Colour values are unitless and represent relative distance above the 95% envelope generated from 1000 random label permutations. Peaks in the surface indicate the spatiotemporal extent of the clustering. That is, a value of one corresponds to the highest autocorrelation value within over the time and distances used in the analysis.

the move-on rules, as seen in the potential 54.1% reduction in hauls with hagfish depredation. The move-on rules for choke and nuisance stocks, or juveniles of target stocks, had less effect but still clearly showed the benefit of avoiding the spatiotemporal clustering of these events. In all cases (except barndoor skates), employment of empirical move-on rules would have led to at least a 25% reduction in the rate of the these negative catch events. Therefore, managers and fishermen can expect significant decreases in discards under these move-on rules. Except for juvenile cod catch (n = 163), the sample sizes of depredation, nuisance, choke and juvenile catches were not large (n = 19–69). We expect that re-running this analysis with larger sample sizes might increase the efficacy of the move-on rules.

Implementation options

Although this study follows in the footsteps of initial calls for and efforts to determine empirical move-on rules (Gardner *et al.* 2008; Lewison *et al.* 2009; Dunn *et al.* 2011), this is the first time such a study has been carried out in cooperation with industry. This collaborative approach will ensure that the results of this study will be the first move-on rules with empirically based times and distances used to directly inform fishing activity. As such, we must consider exactly how these move-on rules might be implemented by the sector managers and fishermen. In mobile gear (e.g. trawls or pelagic longlines), fishermen set and haul a single piece of gear consecutively and can make adaptive decisions based on conditions and the characteristics of the last haul. However, many stationary gears (e.g. anchored sink gillnets or traps) are often set and hauled at one time, limiting how information on catch from one gillnet may be used in determining where to locate the next set. Under these constraints, there are four possible methods for incorporating move-on rules into the use of anchored sink gillnets:

1. 'exploratory fishing' before the gillnets are set and apply the move-on rule based on the exploratory fishing;
2. for move-on rules with temporal extents >1 day, apply the rule in deciding where to fish the next day;
3. when setting all gillnets, separate them by the distance in the move-on rule;
4. if the need to avoid choke species or discards is great enough, investigate the possibility of consecutive sets (i.e. setting and hauling one net at a time).

It is not uncommon for gillnet fishermen to 'explore' with a rod and reel before setting their gear. This exploratory fishing is a quick test of the density of target stocks, and sublegal fish or non-target species. Based on what is found, the fishermen may choose to set his or her nets or move to different fishing grounds. In effect, they implement their own move-on rule. Our study can be incorporated into this exploratory process to offer some guidelines in how far to move. The main issue with relying solely on this method of implementation is that depredation of catch from a rod and reel is far less likely than depredation of catch that remains in an anchored sink gillnet for hours to days. Therefore, this method can only inform catch of juveniles, choke or nuisance stocks. Option 2 (above) would limit fishermen to only implementing move-on rules that have a time element >1 day. Several of the move-on rules developed in this study do have temporal extents >1 day (barndoor skate catch, and flea and hagfish depredation) and could be used in this manner. However, this method would not reduce unwanted catch for all gear deployed at the same time. This would reduce the efficacy of the move-on rule. The third listed option is to proactively separate each gillnet in a trip by the distance specified in the move-on rule. The distribution of distance between consecutive sets in the data set indicated that 43.9% of sets were >1 km away from the last set, 19.6% were >2 km away, and 12.4% were >3 km away. Five of seven of the move-on rules identified in this study recommend moving 3 km or less. Thus, there is some potential to implement this option, although it would clearly mean increasing the average distance between sets and potentially increasing fuel costs. The last option (4) is a significant departure from the current method of fishing and would require substantial education and outreach for fishermen to accept such a fundamental change. However, if the drawbacks are great enough (e.g. the cost to lease more quota is prohibitive), they may consider multiple, shorter, consecutive sets. This method of fishing would be more precautionary than setting all nets at one time and would incur greater costs (e.g. time, fuel) on the part of the fishermen, but may be necessary as fishermen approach quota limits. While these implementation options may be viable, further bioeconomic analysis and discussion with fishermen would be necessary to see which, if any, would be optimal.

To facilitate the development and implementation of move-on rules using this approach, we have added tools for performing spatiotemporal analyses of fishery records to the free, open-source Marine Geospatial Ecology Tools software (MGET; Roberts *et al.* 2010), version 0.8. These tools integrate with the popular ArcGIS software (ESRI 2010) and allow managers to run the analyses on any fishery that has records of landings or discards that include spatial and temporal data.

Empirical move-on rules

The importance of a data-driven process to determining move-on rules is self-evident. Without knowledge of how the species or events of interest are correlated in time and space, managers and fishermen will likely develop rules that either underestimate the degree of autocorrelation and result in less or no decrease in the negative catch, or overestimate the autocorrelation and cause unnecessary economic burden to fishermen (by overly limiting the time/area they can fish in). If the measure is implemented by managers, such inefficiency may also undermine trust between fishermen and managers. Of note is the difference found in the time/distance of autocorrelation in juvenile cod catch in this study (1 day and 2.5 km or ~5.725 nmi^2) as compared to the rules in place under the Scottish conservation credits program (21 days and 50–225 nmi^2). We do not imply that the rule used in the program is incorrect or ineffective, but the difference does suggest a need for further research into possible explanations and consideration of multiple scales of autocorrelation.

One potential reason for the difference between our results and the rules employed in Scotland is their use of threshold values of catch to define an 'event'. That is, they define a juvenile catch event as being a haul that results in more than 40 juvenile cod per hour of fishing (Holmes *et al.* 2011; Needle and Catarino 2011). We define a juvenile catch event as a haul that has any juvenile catch. The development of such catch thresholds should be based on an understanding of the population level effects of the catch, and are beyond the scope of this study. Such thresholds, however, are easily incorporated into an analysis of spatiotemporal autocorrelation and should not limit the use of this technique. Another possible explanation is the different gear examined in the two studies. Our analysis was carried out on anchored sink gillnets, whereas the Scottish studies looked at trawl gear, which inherently covers larger swaths of the seabed.

Broader applicability of empirical move-on rules

In this study, we suggest that, due to the implementation of quotas and sector-based management, catch of choke stocks and discards (both regulatory and market-based) will likely play an increasingly important role in the fishing strategies of New England fishermen. More broadly, they also affect, or are likely to affect, all US fisheries following the passing of the Reauthorization of the Magnuson-Stevens Act of 2006 with its requirements to implement Annual Catch Limits for all fisheries by 2011, and globally as discards policies are reconsidered (e.g. current discussions of a ban on discards under the EC's Common Fisheries Policy). This is particularly true given the continued movement toward catch shares (Arnason 2002; Chu 2009; Jardine and Sanchirico 2012). In an effort to help fishermen and managers deal with these new factors, we offer analyses of spatiotemporal autocorrelation to generate empirical move-on rules that will aid in the efficient fulfilment of quotas. Such rules can simultaneously benefit the fishermen by minimizing lost opportunities for revenue and benefit the target stock by minimizing overages in quotas and capture of juveniles that could lead to growth and recruitment overfishing. The utility of this method is not limited to efficient use of target stocks, but can also be applied to avoid protected species and may offer a much more targeted method of approaching the issue of protected species bycatch than simple time–area closures.

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