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Resilience of a commercial fishing fleet following emergency closures in the Gulf of Mexico

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ABSTRACT

We used high-resolution fisheries-dependent data and a quantitative modeling approach to examine resilience of a commercial reef fish fleet after the *Deepwater Horizon* oil spill (DWH) emergency closures in 2010. Our results indicate that the fleet was largely resilient to the closures, although there were spatially-varying differences in attrition, and concomitant management changes and emergency payouts that likely influenced resilience. Five percent of previously active vessels exited the fleet after DWH (compared to the background annual attrition rate of ~20%). The predicted probability of exiting after DWH was lower for vessels with a pre-closure history of high catch-per-unit-effort, low snapper revenue variability, or low grouper revenue. There was ~80% overlap in pre- to post-DWH effort distribution, although vessels that exited concentrated effort in the north-central and eastern Gulf of Mexico. The Vessels of Opportunity program and other emergency compensation likely ameliorated some of the negative economic impacts from DWH, allowing more vessels to remain in the fleet than may have otherwise. Implementation of gear restrictions and individual fishing quotas leading up to DWH may have also 'primed' the fleet for resilience by removing marginal fishers. This work is novel in its use of high-resolution spatial data, coupled with trip logbooks, to construct quantitative models identifying drivers of fisher resilience after significant and sudden perturbations to fishery resources in the Gulf of Mexico. This work also highlights the need to better understand fisher response to disturbance for long-term fishery sustainability and management.

1. Introduction

Over the past decade, there have been significant shifts in fisheries management in the Gulf of Mexico (GoM) as well as other large-scale and sudden disturbances, with implications for fisheries and coastal communities across the region. Regulatory mechanisms used to manage the commercial reef fish fishery have included gear restrictions, closed seasons, spatial closures, size limits, per-trip catch limits, and limited access individual fishing quota programs (IFQs) for two major sectors, Red snapper and Grouper-Tilefish. Additionally, in 2010, the GoM was struck by the largest accidental oil spill in U.S. waters to date. Starting on 20 April 2010, an estimated 4.9 million barrels of oil (~206 million U.S. gallons) spilled from the *Deepwater Horizon* (DWH) oil well into the GoM, until the wellhead was finally capped 87 days later on 15 July. To ensure that oil-contaminated seafood did not reach market, the National Marine Fisheries Service (NMFS) instituted a series of emergency fishing closures, from 2 May through 15 November 2010. The closures were substantial in areal extent, reaching a maximum of just over 229,000 km^2 (or 37% of the U.S. portion of the GoM) on 2 June 2010 (Fig. 1). By 15 November 2010, all closures were removed except the area immediately around the wellhead, and by 19 April 2011 all closed areas had been reopened. These closures were successful in that no tainted seafood was reported to have entered the supply chain (Lubchenco et al., 2012).

Research since DWH has demonstrated negative effects on the health of residents in coastal communities impacted both directly and indirectly by the spill, often disproportionately for those individuals and families involved in the fishing and seafood industries (Grattan

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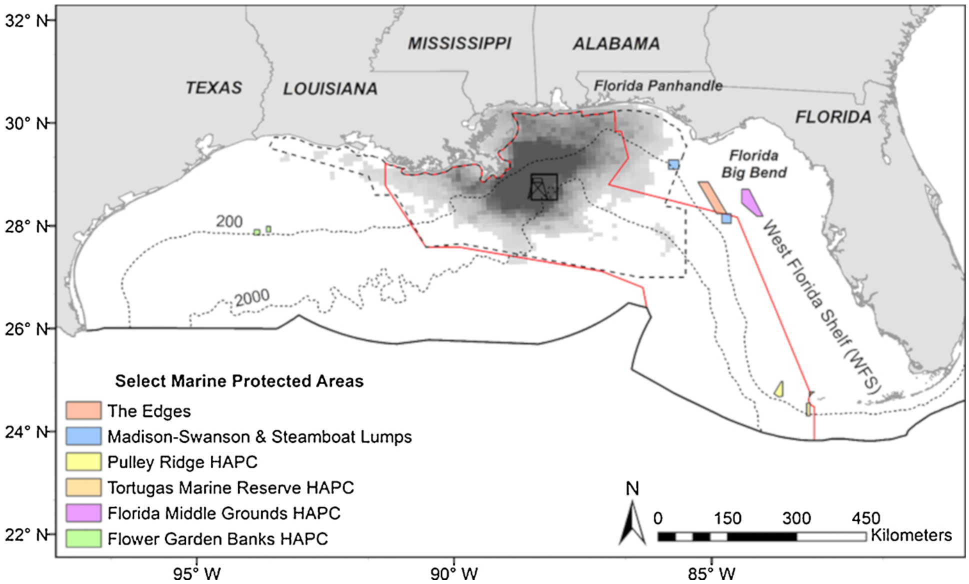

Fig. 1. Study region and DWH fishing closures extent. The location of the DWH wellhead is marked with an oil derrick symbol and the surface expression of the DWH oil spill is shown in gray tones, with the darker colors representing longer exposure to oil. The maximum extent of the DWH emergency fishing closures on 2 June 2010 (229,270 km^2) is delineated with the solid red polygon, the dotted black polygon is the extent of the fishing closures on 22 July 2010 (149,026 km^2), and the solid black square is the closure immediately around the wellhead (2,697 km^2) that was closed until 19 April 2011. Marine protected areas shown include The Edges, Madison-Swanson, and Steamboat Lumps, Pulley Ridge, Tortugas Marine Reserve, Florida Middle Grounds, and Flower Garden Banks National Marine Sanctuary. The 200 m and 2000 m isobaths are labeled and marked with dotted lines and the U.S. Exclusive Economic Zone (EEZ) is marked with a solid black line. Note that the southern end of the 2 June fishing closure intersects the EEZ. All fishery closure data and marine protected area polygons were downloaded from NOAA Fisheries Southeast Regional Office (available online at: http://sero.nmfs.noaa.gov/deepwater_horizon/closure_info/index.html and http://sero.nmfs.noaa.gov/maps_gis_data/fisheries/gom/GOM_index.html) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

et al., 2011; Lee and Blanchard, 2011; Cope et al., 2013). However, direct and indirect effects on fishers' livelihoods (e.g., leaving the fleet temporarily or permanently) and drivers of resiliency to the oil spill (e.g., diverse economic opportunities outside of fishing) are not well studied. There are few studies that explicitly report changes in landings, catch composition, or revenue after DWH (McCrea-Strub et al., 2011; Sumaila et al., 2012; Murawski et al., 2016). However, these studies used coarse-resolution spatial and temporal data, thus limiting the interpretation and conclusions about how fishers responded during and after the oil spill. This study used trip logbook, high-resolution vessel monitoring system (VMS) satellite tracking, and quantitative modeling approaches to identify potential drivers of fisher resilience, to quantify the probability of leaving the fleet, and identify spatial shifts in fishing effort after the DWH oil spill closures.

The main objective of our analysis was to construct a general linear model (GLM) predicting the probability of a vessel exiting the fleet after emergency closures. We expected that vessels with a history of fishing outside of closure boundaries, high aggregate CPUE/revenue, and/or less variable aggregate CPUE/revenue would be the *least* likely to exit the fleet. These expectations are consistent with existing literature on the importance of income stability for fisher success (e.g., Hackett et al., 2015) and were drawn from our own assumptions about displacement impacts from DWH closures and the ability of high earning/low variability fishers to withstand adverse impacts from the oil spill.

Understanding the range and magnitude of fishers' responses to perturbations — including regulatory change and human-induced environmental disasters — is critical for designing effective management and disaster response policies that can meet biological, ecological, economic, social, and sustainability objectives. Given the importance of commercial fishing to the economic, cultural, and social well-being of many coastal communities, this research is of broad interest to fishing and tourism sectors, fisheries managers, researchers, government agencies, oil spill response agencies, and policy makers.

2. Materials and methods

2.1. Overview

Fleet resilience was measured at the vessel level, and quantified as remaining in the fleet or not after DWH closures. Resilience in this context is defined as the ability to absorb, adapt to, or cope with disturbance over time. Individual vessel-level data on catch and revenue history, history of fishing location relative to emergency closures, and factors such as gear types used within and between trips, states where catch was landed, trip duration, and species group targeted were used as linear model predictors to assess the probability of exiting after DWH (Table 1). We used VMS data to identify and quantify the pre-closure spatial distribution of effort relative to fishing closures. The VMS technology provides a geospatial reference point for a vessel approximately every hour for the duration of every trip, and has been required on all vessels with a commercial reef fish permit since 2007. At the time of this writing, there are over 760 valid active limited access commercial permits for GoM reef fish, making this a comprehensive and valuable data set.[2] Complementary vessel-level trip logbooks and onboard observer data were also used to define speed rules for discriminating fishing activity, quantify pre-closure fishing productivity, and determine if a vessel exited the fleet after closures. The steps to select and match logbook and VMS data, characterize fishing history, and fit the GLM are described below and in greater detail in the Online Supplementary Appendices.

2.2. VMS reporting consistency

VMS locations in the GoM are reported approximately every hour for the duration that the transponder is active. However, the VMS data are patchy in places, with some vessels having highly irregular tracking records. In order to eliminate lower quality reporting vessels, a linear model was fit to each individual vessel's VMS record (from 2006 to 2013), with ordered record number as the predictor and timestamp of the location record as the response. Using this approach, a perfect VMS record would make a straight line (i.e., $r^2 = 1$) while gaps in the VMS record would cause discontinuities in the ordered data series and a decrease in the r^2 value of a fitted regression model for that vessel. The

[2] NOAA Fisheries Southeast Regional Office. Permits Office. List of Frequent FOIA Requests Regarding Permits, Vessels, and IFQ. Limited Access Commercial Permits: Gulf of Mexico Reef Fish. Accessed 11 November 2018. Available online at: https://sero.noaa.gov/operations_management_information_services/constituency_services_ branch/freedom_of_information_act/common_foia/index.html.

Table 1
Factors and corresponding model predictors considered as inputs into the logistic general linear models for quantifying fisher resilience after DWH fishing closures.

Factor	Model Predictor(s)
Distribution of pre-disturbance effort (1 January 2008-1 May 2010) relative to closures	Vessel-level spatial impact metric aggregated from respective trips
Aggregated pre-disturbance fishing history characteristics	Median trip duration (days)
	Primary gear used (Top gear)
	Primary species group landed (Top group)
	Primary landing state (Top state)
Aggregated pre-disturbance fishing history characteristics coded as dummy variables (0/1)	Multiple gear types used within a trip
	Multiple top gear types used between trips
	Multiple top groups between trips
	Multiple landing states between trips
Aggregated pre-disturbance productivity	Median total CPUE
	Total CPUE variability
	Median total revenue
	Total revenue variability
	Median snapper revenue
	Snapper revenue variability
	Median grouper revenue
	Grouper revenue variability
Interactions considered	Total CPUE × total CPUE variability
	Total revenue × total revenue variability
	Median snapper revenue × snapper revenue variability
	Median grouper revenue × grouper revenue variability
	Total CPUE × top group
	Total revenue × top group
	Total revenue variability × top group
	Total CPUE variability × top group
	Spatial impact × CPUE
	Spatial impact × CPUE variability
	Spatial impact × revenue
	Spatial impact × revenue variability
	Spatial impact × top group

Note: Aggregated pre-closure values contain trips from 1 January 2000-1 May 2010, except for the spatial impact metric since VMS data were not available until 2007. All revenue values were inflation adjusted to 2008 U.S. dollars.

VMS data used in this study were filtered by selecting vessels with a high r^2 value (i.e., a consistent record; r^2 = 0.75 or greater) and 10 or greater total VMS records.

2.3. Determining fishing activity

The VMS data (Rivero, 2015) were filtered to retain only active fishing locations, as determined by: (1) linking VMS records to logbook trips based on a unique vessel identifier and trip start and end dates, (2) filtering VMS-logbook linked data to the times of peak fishing activity as quantified from observer data, and (3) applying empirically-determined “speed filters” based on the cumulative distribution of ranked vessel speeds (see Online Appendices A and B). Based on the cumulative distributions of VMS speeds, speed rules of 1–4 m/s were used for both bottom longline and vertical line gear (i.e., handline or bandit-reel). Based on observer peak fishing activity, time filters of 6:15 AM to 10:45 PM and 7:45 AM to 8:00 PM were applied for bottom longline and vertical line gears, respectively. After identifying fishing activity with the time and speed filters, an additional 5.56 km (three nautical mile) coastal “buffer” was added to avoid false positives for fishing activity near the coast. Records that were on land, in port, outside the GoM basin, or deeper than 200 m (where reef fishing is highly unlikely to occur) were also eliminated. In addition, vessels with fewer than three active fishing locations after filters were applied were removed from the data to allow for proper calculation of spatial metrics in later analyses.

2.4. Fishing history relative to closures

We calculated a metric of pre-closure effort spatial distribution relative to DWH fishing closures to include fishing location history in the GLM. A vessel’s pre-closure VMS record (1 January 2008 through 1 May 2010) was used to construct a metric of fishing relative to the closures. The metric ranged from 0 to 1, which was the proportion of each vessel’s pre-closure VMS fishing records that occurred inside an area subsequently closed during DWH. There was, however, the additional challenge of accounting for changing spatial extent of closures over time. To solve this, a heat map of closure proportion for the DWH fishing closures was created in ArcGIS10.3 (ESRI, Redlands, CA, USA) by: (1) importing and overlaying the polygons of all emergency closures, (2) calculating a cumulative number of days closed in each region based on all overlapping closure polygons, and (3) dividing the cumulative days closed in each area by the total number of days closures were enacted (352 days from 2 May 2010 to 19 April 2011; Fig. 2). Values for closure proportion therefore ranged from 0 to 1 (e.g., an area that was never closed was assigned a value of 0 and the area closed for 352 days was assigned a value of 1). Pre-closure VMS fishing records for all trips were overlaid on the heat map, and the underlying closure proportion values were assigned to the VMS records. A trip-level median spatial distribution metric was calculated using all VMS records from a given trip, and a vessel’s aggregate pre-DWH spatial distribution metric was calculated as the median value from all respective trips.

2.5. Logbook data

Logbook records from 2000 to 2014 were first filtered by eliminating trips that reported no vessel length, landings, revenue, or effort (i.e., average hooks per line, average number of lines used, or total number of sets), and duplicate records (less than 1% of all logbook records) were removed based on the unique trip identifier assigned to records by the NMFS Southeast Fisheries Science Center. Only trips reporting bottom longline or vertical line as the top-revenue producing gear were used in analyses, since these are the main gear types used in this fishery (Scott-Denton et al., 2011), and represent 89% of logbook-reported trips from 2000 to 2014. Vessels with anomalous gaps in their VMS reporting consistency (as described above) were removed. Vessels with fewer than three total trips in the logbook record (from 2000 to

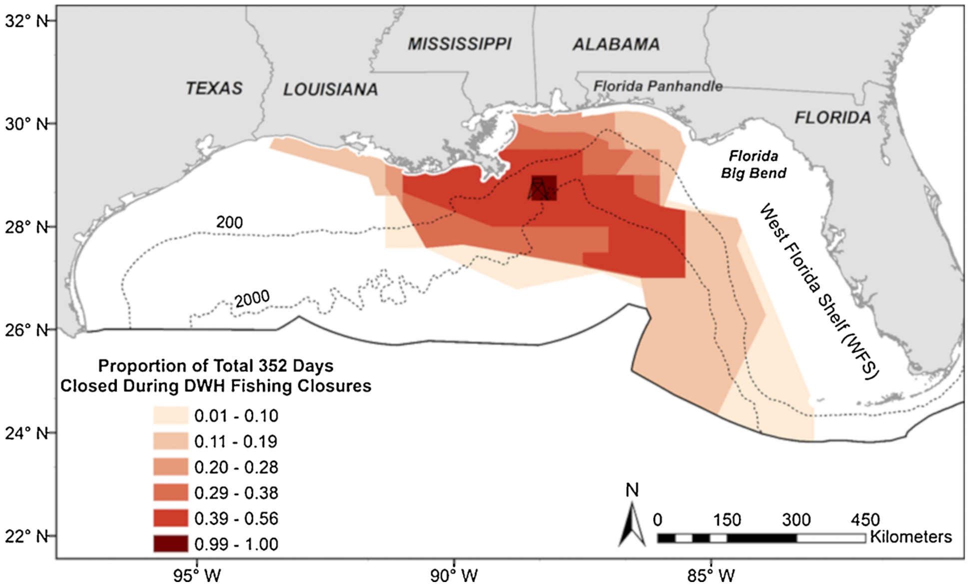

Fig. 2. Cumulative days closed, expressed as a proportion of total days closed for each emergency closure region during the DWH oil spill. Darker colors represent a larger proportion of cumulative days closed. Symbols are as in Fig. 1. All polygons of fishery closures were downloaded from NOAA Fisheries Southeast Regional Office (freely available online at: http://sero.nmfs.noaa.gov/deepwater_horizon/closure_info/index.html).

2014) or fewer than three VMS points in the total record (from 2008 to 2012) were also removed. Attrition rates were calculated based on VMS and logbook data after removing vessels based on VMS reporting consistency, but before selecting vessels for the final GLM analysis.

Only data for snappers, groupers, tilefishes, jacks, and triggerfish were used to quantify catch and revenue. The five species groups were specifically chosen due to their importance as commercial fisheries, availability and consistency of data, and the large percentage of all trips reporting landings for these groups (79–91% of trips from 2000 to 2014 reported one of the groups as the top landed; Table 2). The five species groups are also managed together under the Gulf of Mexico Reef Fish Fishery Management Plan. Total revenue and total landings were calculated for each trip as the sum of reported values for the respective species in each of the five groups (Table 3). Trips that had zero total landings (calculated from the five species groups) were eliminated, under the assumption that the trips were not targeting reef fish. Total CPUE was calculated for each logbook trip as the total calculated landings (for all five species groups combined) divided by the reported average number of hooks used per set. Snapper and grouper species landings, revenue, and CPUE were also calculated for each trip. All CPUE and revenue data were natural log ($\log_e$) transformed to linearize relationships and meet normality assumptions of regression analyses.

Total calculated revenue, snapper revenue, and grouper revenue for each trip was inflation adjusted to 2008 U.S. dollars ($2008) using the United Nations Food and Agriculture Organization (FAO) fish price

Table 2
Top species group landed as a percentage of all logbook trip data from 2000 to 2014.

Top group landed	% Total logbook trips [a]	% Select logbook trips [b]
Shallow Water Groupers	35.72	43.32
Mid-depth Snappers	29.14	36.16
Shallow Water Snappers	9.09	5.86
Coastal Migratory Pelagics	16.04	4.64
Deep Water Groupers	3.03	3.82
Sharks	3.4	2.7
Jacks	1.31	1.39
Grunts And Porgies	1.03	0.95
Tilefishes	0.55	0.66
Triggerfishes	0.15	0.18
Other Species	0.28	0.14
Tunas	0.15	0.11

Note: Bolded groups were used in general linear model (GLM) analyses. Individual species included in each group are listed in Table 3.
[a] 2000-14 logbook records for all gears (n = 162,697).
[b] 2000-14 logbook records reporting bottom longline, bandit-reel, or handline as the top gear, and filtered for vessel VMS reporting consistency (n = 103,216).

Table 3
Species included in each group used in general linear model (GLM) analyses.

Top group	Species included
Shallow Water Snappers	Hogfish
	Lane snapper
	Mangrove snapper
	Mutton snapper
	Other snappers
	Yellowtail snapper
Shallow Water Groupers	Black grouper
	Gag
	Other groupers
	Red grouper
	Red hind
	Rock hind
	Scamp
	Yellowfin grouper
	Yellowmouth grouper
Mid-depth Snappers	Black snapper
	Dog snapper
	Mahogany snapper
	Other mid snappers
	Queen snapper
	Red snapper
	Schoolmaster
	Silk snapper
	Vermilion snapper
Deep Water Groupers	Misty grouper
	Snowy grouper
	Speckled hind
	Warsaw
	Yellowedge grouper
Jacks	Greater amberjack
	Lesser amberjack
	Other jacks
Tilefishes	Blackline tilefish
	Golden tilefish
	Goldface tilefish
	Gray tilefish
	Other tilefish
Triggerfish	Spadefish
	Triggerfish

index (FPI) price series (Tveterås et al., 2012; y available online at http://www.fao.org/in-action/globefish/fishery-information/resource-detail/en/c/338601/). Analogous to a consumer price index, the FPI collapses price and quantity information into one number that tracks change in seafood price. The FPI is an improvement over other food commodity indices in that it incorporates aquaculture production, import and export flows, and the extent of international trade competition for 608 unique trade data categories of fish and seafood. The value of the FPI for 2008 (i.e., FAO value of 136) was set to 100 as the standard and all other FPI values were scaled accordingly (i.e., multiplied by 0.74). Inflation-adjusted revenue (total, snapper species, and grouper species) for each trip *i* was calculated based on total or species group revenue for the trip (R_i) divided by the scaled FPI for the year *j* in which catch was landed (FPI_j):

$$Inflation\ adjusted\ R_{i,j} = (R_i/Scaled\ FPi_j) \times 100 \tag{1}$$

All CPUE and revenue values were additionally standardized to account for effects of vessel size, as larger vessels have the capacity to hold more fish, make longer trips, and therefore report greater landings or revenue overall. To eliminate this potential confounding factor, untransformed logbook data were divided by a fishing power coefficient (Table 4). Fisher's Natural Breaks Classification was applied to logbook data from 2000 to 2014 (n = 96,668 records) using the *classInt* package in R (Bivand et al., 2015) to obtain empirically-determined size bins for four vessel size classes. Fishing power coefficients for each variable *a* (CPUE, inflation-adjusted revenue, and landings) and vessel size class *b* were then calculated based on coefficients from linear regressions of the $\log_e$-transformed data vs. vessel length (Murawski et al., 2005):

$$F_{a,b} = e^{regression\ coefficient\ estimate + (0.5 \times coefficient\ std.\ error)} \tag{2}$$

To ensure that there was no relationship between the standardized data and assigned vessel class, an ANOVA was performed on $\log_e$-transformed standardized data vs. vessel size class after each transformation and confirmed visually with boxplots and scatterplots. All subsequent analyses with logbooks used data that were vessel-size standardized and $\log_e$-transformed.

2.6. Modeling fishers' response to DWH closures

A logistic GLM was fit to predict the probability of individual vessels exiting the fleet after the DWH closures in 2010. The vessel-level spatial distribution metric (see Section 2.4) and a range of vessel-level productivity data were used to fit the model (Table 1). Only those vessels that had (1) a valid matching pre-closure spatial impact metric (i.e., calculated from trips with more than three VMS records), and (2) trips in 2008, 2009, and 2010 (with a start date before the 20 April 2010 blowout) were used to fit the GLM (n = 320 vessels). If a vessel did not have any logbook trips with a start date on or after the initiation of emergency closures (2 May 2010), it was considered as having exited. Vessels that returned to the fleet in 2011 or 2012 after the closures were not included in the analysis; there were too few vessels in this category to create a statistically sound third "returned" category.

For each vessel, we used logbook trips to calculate aggregated pre-closure (1 January 2000 through 1 May 2010) median total CPUE and revenue, median snapper CPUE and revenue, median grouper CPUE and revenue, between-trip variability (standard error) in all CPUE and revenue terms, and median trip duration. We also identified primary and secondary top gear types used by each vessel, primary and secondary landing states, and primary and secondary top species group landed for use as model predictors in the GLM. Top species group and top gear type were reported in logbooks, and are considered those that produced a plurality of revenues for a given trip. Mississippi and Alabama were consolidated into one state group due to low sample size. Dummy variables (represented as 0 or 1) for multiple gear types used within a trip, multiple top gear types used between trips, multiple top groups reported between trips, and multiple landing states used between trips were also included as model predictors.

Linear model predictors were selected and validated using a series of tests. Before proceeding with fitting the GLM, potential collinearities between model predictors were tested with a variance inflation factor (VIF) test (Zuur et al., 2010), implemented in R with the Highland Statistics Ltd. course files library (Zuur et al., 2009). The VIF test was performed on numerical model predictors based on all trips before closures (n = 47,703 trips from 1 January 2000 – 1 May 2010). Values above three were considered highly collinear, and removed from the pool of model predictors used to fit the GLM. Predictor variables were removed sequentially, with the largest VIF removed first, and the test repeated on the new set of model predictors until all VIF values were below three. In addition, a pairwise Pearson correlation test (without a multiple comparison p-value adjustment) was performed between all pairs of predictors retained after the VIF test, using the *psych* package in R (Revelle, 2017) and visualized with a correlation scatterplot using the *gclus* package (Hurley, 2012), to ensure that model predictors were not significantly correlated.

Backwards selection of an optimal model using Akaike's Information Criterion (AIC) was conducted from the full model of all terms (including appropriate interactions; Table 1) in R using the native *stats* package. Terms were sequentially dropped based on comparison of the AIC values and a likelihood ratio test (testing for significant differences in scaled deviance) between models. Predictors were removed if the reduced model resulted in a smaller AIC and non-significant changes ($p > 0.05$) in deviance; terms that reduced the AIC the most were removed first. At the same time, each iteration of model reduction was tested for omitted variable bias (i.e., that the remaining predictors did not "absorb" some of the effect of the removed term), by comparing the coefficients of all remaining terms between sequential models and with the full (starting) model. After each predictor removal, the model was re-evaluated, and the process was repeated until further iterations resulted in large increases in coefficients (i.e., there was evidence of omitted variable bias). Based on the omitted variable bias test, nine iterations of backward selection were used to select the final model predictors. Because of the skewed nature of the response (i.e., many more vessels remained than exited), a complementary log-log link function was used for all models. 'Bottom longline' and 'Florida' were used as the standards for gear type and landing state, respectively (GLM coefficients = 1). A Wald Chi-square test was conducted with the *aod* package (Lesnoff and Lancelot, 2012) after the GLM to compare differences among levels of primary gear type and landing state.

Plots of standardized GLM residuals using the *DHARMa* package

Table 4
Fishing power coefficients used for standardizing model predictors to vessel size.

Vessel length (m)	Vessel category	Total revenue	Total landings	Total CPUE	Snapper revenue	Snapper landings	Snapper CPUE	Grouper revenue	Grouper landings	Grouper CPUE
[4.87-9.9]	1	1	1	1	1	1	1	1	1	1
(9.9-12.63]	2	3.26	3.18	1.02	2.00	1.93	0.62	10.12	8.28	2.66
(12.63-16.46]	3	7.12	7.06	0.12	5.61	5.27	0.09	10.89	9.07	0.15
(16.46-26.21]	4	9.15	8.92	0.15	22.07	18.56	0.32	1.90	1.81	0.03

Note: Vessel size class 1 was the standard for all calculations. All size class intervals were closed on the right.

Table 5
Results from the general linear model predicting the probability of exiting the fishery.

	Coefficient	Std. Error	P
(Intercept)	−7.79	4.99	0.12
Median total CPUE	−0.97	0.40	0.01 *
Snapper revenue variability	2.98	1.41	0.03 *
Median grouper revenue	0.67	0.31	0.03 *
Median total revenue	0.78	0.69	0.26
Total revenue variability	22.34	19.26	0.25
Total CPUE variability	−12.74	7.11	0.07
Median trip length (days)	−0.29	0.19	0.12
Median vessel-level spatial impact	34.10	37.12	0.36
Landed state: LA	−14.46	2487.9	1.00
Landed state: MS/AL	4.53	2.55	0.08
Landed state: TX	−15.48	3188.1	1.00
Top Gear: Bandit	1.79	2.23	0.42
Top Gear: Handline	1.76	2.34	0.45
Multiple top groups landed: Y	−1.05	1.05	0.32
Median total revenue × total revenue variability	−4.55	3.17	0.15
Median total CPUE × total CPUE variability	2.55	1.78	0.15
Median total revenue × median vessel-level spatial impact	−3.69	5.01	0.46
Median total CPUE × median vessel-level spatial impact	−4.51	2.82	0.11
Total revenue variability × median vessel-level spatial impact	31.28	28.09	0.27

Note: Results are given on the scale of the link function (log odds). Significant model predictors (at an alpha of 0.05) are marked with an asterisk. Base levels for the categorical predictors were Florida ('Landed state'), Longline ('Top Gear'), and not reporting multiple species groups between trips ('Multiple top groups landed'). All analyses were run with natural log transformed values and all revenue values were inflation adjusted to 2008 U.S. dollars.

(Hartig, 2018) were used to identify potential outliers and validate the final GLM. *DHARMa* uses a simulation-based approach, similar to a parametric bootstrap, which transforms GLM residuals to a standardized scale (Hartig, 2018). Residuals were tested for uniformity (i.e., goodness-of-fit) with a bootstrapped simulation of residuals, Q-Q plot of expected vs. observed residual values, a Kolmogorov-Smirnov uniformity test, and quantile regression of residuals vs. model fitted values. Residuals were also plotted against each significant model predictor to identify potential outliers and any patterns in the residuals, which may indicate the need for smoothers in the model. One outlier for high revenue variability was identified and removed using residual validation plots, and confirmed as an outlier ($p < 0.001$) with the Grubb's test in the *outlier* package in R (Komsta, 2011). The final GLM was refit after the outlier was removed.

The significance of the overall GLM was tested by comparing the residual deviance with the deviance of a null model (i.e., a model with just an intercept). The test statistic was the difference between the residual deviance for the GLM and the null model, tested with a Chi-square distribution with degrees of freedom equal to the difference in degrees of freedom between the GLM and the null model (i.e., the number of predictor variables in the model). Lastly, logbook data were used to assess differences in trip patterns between vessels that remained and those that exited. Primary landing state, primary and secondary gear used, and the composition of species landed were compared between the vessels in each group.

2.7. Post-oil spill changes in effort distribution

A spatial difference index (Lee et al., 2010) was calculated to quantify the overall difference in effort distributions between years and gear types. Using the *raster* package, each raster layer was normalized so that the sum of all cell values was equal to 1. The per-cell absolute difference between two layers was then calculated, summed over the entire study region, and divided by two. This provided an index of difference that varied from zero, such that an index of 0 represented identical spatial distribution of fishing activity, and 1 represented maximum difference, or no overlap, in spatial use.

Differences in the spatial distribution of fishing effort were then mapped for: (1) pre-closure distribution (1 January 2008 through 1 May 2010) of vessels that exited the fleet vs. those that remained, and (2) the pre-closure vs. post-closure (2 May 2010 through 28 December 2012) distribution of remaining vessels. All effort densities were first calculated as the number of VMS records per 0.15°-squared grid cell, using the *raster* package in R (Hijmans et al., 2016). Grid cells with less than three unique VMS records (regardless of trip or vessel) were reassigned as "NA" and not mapped, to ensure confidentiality of the data. For ease of comparison and visualization, densities of remaining cells were rescaled (ranging from 0 to 1) relative to the maximum value. Changes in spatial distribution (based on relative effort density) were then calculated as the difference between individual density layers. A difference of 0 indicated no change in relative density, or complete overlap in distribution, while a value of 1 or -1 indicated maximum difference, or no overlap in spatial distribution.

3. Results

3.1. Model fitting

There were 1,302 unique vessels in the VMS data set, reduced to 1,104 unique vessels once the consistency filter was applied (~85% of all unique vessels). The mean reporting consistency r^2 value for these vessels was 0.96. Further filtering of vessels for reporting criteria and inclusion in the GLM resulted in a final 320 vessels used to fit the GLM (~25% of all unique vessels). Correlation and VIF tests resulted in retaining trip length (in days), total revenue, total CPUE, snapper revenue, grouper revenue, and mean trip-level spatial impact metric. All final VIF values ranged from 1.1 − 1.6. Although total revenue and CPUE were significantly correlated ($p < 0.001$), the magnitude of correlation was small (correlation = 0.08) and so both were retained for the GLM. A total of 319 vessels were used to fit the GLM, 17 of which exited after DWH (~5%). The final GLM used median CPUE, snapper revenue variability, and median grouper revenue as significant to predict the probability of exiting the fleet (Table 5). Smoothers for median revenue, revenue variability, median CPUE, CPUE variability, snapper revenue variability, and median grouper revenue were tested; terms were either insignificant ($p > 0.05$), or significant with a smoothing term that did not differ from the linear model (effective d.f. approximately = 1) so no smoothers were added to the model. The GLM was significant overall ($\chi^2 = 49.9$, d.f. = 19, $p < 0.001$) and model residuals were uniform based on bootstrapping simulated values ($p = 0.79$) and a Kolmogorov-Smirnov test ($p = 0.52$), indicating a good fit and a correctly specified model.

Vessels with greater overall median CPUE were less likely to exit ($p = 0.01$), while vessels with greater snapper revenue variability or median grouper revenue were more likely to exit ($p = 0.03$; Fig. 3). The rate of exit after closures was much lower than the background rates of annual attrition seen in logbook and VMS data (Table 6), both prior to and after these closures. From 2000 through 2014, the mean rate of attrition in logbook data was 14% annually, and both logbook and VMS rates of attrition were ~20% annually from 2008 − 2012. Both logbook and VMS data showed evidence of consolidation in the fleet, with fewer total trips and fewer total vessels over time (Table 6). At the same time, there was a peak in vessel exit of 27% from 2009-10 (i.e., during DWH) and a peak entrance of vessels of 18% from 2010-11 (i.e., one year after DWH). The percent exit annually also increased over time, from 8% in 2000 to 18% in 2013, and had a mean of 21% annually after 2010.

Gear type, state landed, and spatial history of a vessel (i.e., the time spent fishing inside the closure region previous to the closure date) were not significant in the GLM, and a Wald test revealed that there was no difference in probability between vessels reporting primarily

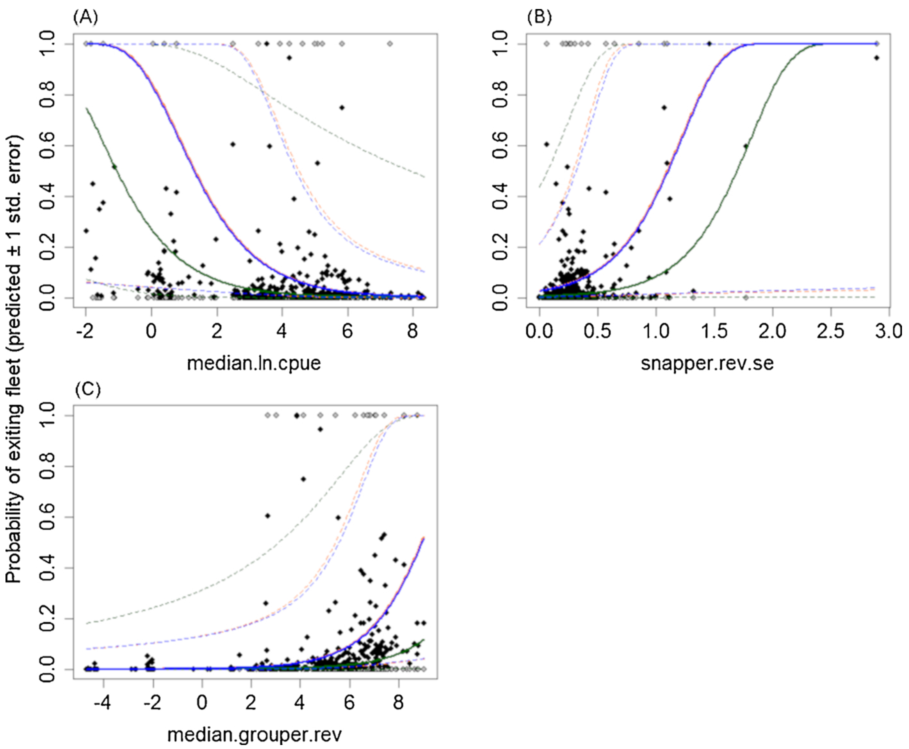

Fig. 3. Results from the general linear model, predicting the probability of exiting the fishery. Probability is shown as a function of (A) median total CPUE (median.ln.cpue), (B) snapper revenue variability (snapper.rev.se), and (C) median grouper revenue (median.grouper.rev). Only predictors that were returned as significant in the GLM are shown. Observed data (exited/remained; 1/0) are in open circles, model predicted values are in filled black circles. Solid lines are the model predicted values (holding all other model predictors at the median or base level) and dashed lines are ± 1 standard error. Blue = handline, orange = bandit-reel, green = longline (model base). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

handline or bandit-reel ($\chi^2 = 0.64$, d.f. = 2, p = 0.72) or among vessels reporting landing primarily in Texas, Louisiana, or Mississippi/Alabama ($\chi^2 = 3.2$, d.f. = 3, p = 0.37). However, comparisons between vessels that exited and remained suggest that there may be a geographic pattern to the probability of leaving. Vessels that exited used either Florida or Mississippi/Alabama to land catch, and a majority of vessels that exited landed catch primarily in Florida (88%). At the same time, 79% of vessels that remained landed catch primarily in Florida as well, and the top three counties of landing in Florida were the same between vessels that remained and exited: Pinellas, Bay, and Franklin (Table 7). Similarly, of the 17 vessels that exited post-DWH, 6 (35%) reported longline as the primary top gear, 4 (24%) reported bandit-reel as the primary top gear, and 7 (41%) reported handline as the primary top gear (Fig. 4). In comparison, 46 remaining vessels (15%) reported longline, 147 (49%) reported bandit-reel, and 109 (36%) reported handline as the primary top gear. Handline was the most common secondary top gear for vessels that remained (47%) and bandit-reel was the most common for those vessels that exited (53%). An equal number of vessels (˜23%) reported no secondary top gear (i.e., they only reported one top gear for all trips).

3.2. Changes in effort distribution

The difference in pre-DWH effort distribution among vessels that

Table 6
Number of unique vessels and rates of vessel entry and attrition as calculated from the logbook and VMS data.

	$Year_i$ -$Year_{i+1}$	Number of unique vessels in $Year_i$	% Remaining	% Exited	% Entering
Logbook	2000-2001	417	91.6	8.4	11.4
	2001-2002	431	93.5	6.5	14.3
	2002-2003	470	90.2	9.8	10.5
	2003-2004	474	92.2	7.8	14.5
	2004-2005	511	89.6	10.4	13.6
	2005-2006	530	88.7	11.3	14.9
	2006-2007	552	86.6	13.4	11.5
	2007-2008	540	85.7	14.3	14.7
	2008-2009	543	86.7	13.3	15.3
	2009-2010	556	73.0	27.0	11.2
	2010-2011	457	79.9	20.1	18.3
	2011-2012	447	82.1	17.9	15.0
	2012-2013	432	78.0	22.0	11.5
	2013-2014	381	81.4	18.6	13.6
	2014	359	n.a.	n.a.	n.a.
	Mean 00-14	473	85.7	14.3	13.6
	Mean 08-12	487	80.4	19.6	15.0
VMS	2008-2009	516	84.3	15.7	15.7
	2009-2010	516	71.9	28.1	12.5
	2010-2011	424	80.4	19.6	17.6
	2011-2012	414	80.4	19.6	14.8
	2012	391	n.a.	n.a.	n.a.
	Mean 08-12	452	79.3	20.7	15.2

Note: Attrition rates were calculated after removing vessels based on VMS reporting consistency and before selecting vessels for use in the GLM.

Table 7
Primary state and Florida county (if applicable) used for landing catch during pre-closure trips (for vessels used to fit the GLM only).

Status after DWH	Primary state for landing catch	# of vessels	Percentage
Exited	FL	15	88.2
	MS/AL	2	11.8
Remained	FL	239	79.1
	LA	29	9.6
	TX	18	6.0
	MS/AL	16	5.3
	Primary county of landing (if landing in FL)	# of trips	Percentage
Exited	Pinellas	864	59.1
	Bay	189	12.9
	Franklin	123	8.4
	Monroe	112	7.7
	Taylor	67	4.6
	Lee	28	1.9
	Dixie	22	1.5
	Levy	22	1.5
	Wakulla	16	1.1
Remained	Pinellas	8303	25.7
	Bay	6040	18.7
	Franklin	3192	9.9
	Escambia	2972	9.2
	Okaloosa	2724	8.4
	Wakulla	2068	6.4
	Monroe	1934	6.0
	Lee	1181	3.7
	Manatee	1038	3.2
	Taylor	631	2.0
	Citrus	507	1.6
	Levy	418	1.3
	Pasco	382	1.2
	Hillsborough	347	1.1

Note: State and county of landing were reported in logbooks. Only counties at 1% or greater are shown.

exited vs. remained was moderate. The overall pre-closure (2008–2010) spatial difference index between the groups was 0.55, meaning there was ˜45% overlap in space use before closures. This overall similarity was only slightly higher than the spatial difference index in 2008 (0.63 = 37% overlap) and 2009 (0.60 = 40% overlap). The greatest overall difference in relative effort density was 0.95 (i.e., almost no overlap) offshore of the central Florida Peninsula, due to a much greater relative density in the area for remaining vessels (Fig. 5). There was also a difference in geographic distribution for those vessels that remained vs. exited: effort was distributed throughout the GoM before closures for vessels that remained (Fig. 5A), while effort was concentrated in the north-central and eastern GoM for those that exited (Fig. 5B).

The fleet displayed a largely similar effort distribution before and after closures, quantified as an 80% overall similarity in space use for remaining vessels, and gear-specific similarity ranging from 77 to 79%, including a return to fishing grounds that were inside closure boundaries. Vessels that remained in the fleet after DWH had a similar spatial distribution after the initiation of fishing closures. The overall spatial difference index for these vessels was 0.21, meaning that there was a ˜80% overlap in space use from before to after closures. The spatial difference index for remaining vessels by gear type was slightly lower than the overall value, but still indicated no significant shifts in spatial distribution post-closure: 0.22 for vertical line (79% overlap) and 0.23 for bottom longline (77% overlap). The maximum absolute difference in relative effort density from before to after closures was 0.59, and was centered on the 200 m isobath off the Alabama coast. This pattern was driven largely by a post-closure reduction in relative effort density off the Alabama coast, just northeast of the DWH wellhead (blue pixels in Fig. 6). Effort also shifted from offshore (near the 200 m isobath) to nearshore along Alabama and the Florida Panhandle, and slightly south/southeastward along the mid and southern West Florida Shelf (red pixels in Fig. 6). The greatest increase in post-closure density was along the southern West Florida Shelf, with an absolute difference of 0.43 (Fig. 6).

4. Discussion

4.1. Major findings

We found that vessels with a record of higher CPUE, lower snapper revenue variability, or lower grouper revenue were the *least* likely to exit after DWH closures. While there were regionally varying outcomes for individual fishers — with a greater concentration of exiting vessels in the north-central and eastern GoM — the overall attrition rate after DWH was well below what was expected based on the background annual attrition rate alone (5% vs. 14–20%). Given the magnitude of the oil spill on the environment, businesses, tourism, and the seafood industry in the GoM, this is a surprising and significant result. Still, once closures were removed there was a decrease in relative effort density

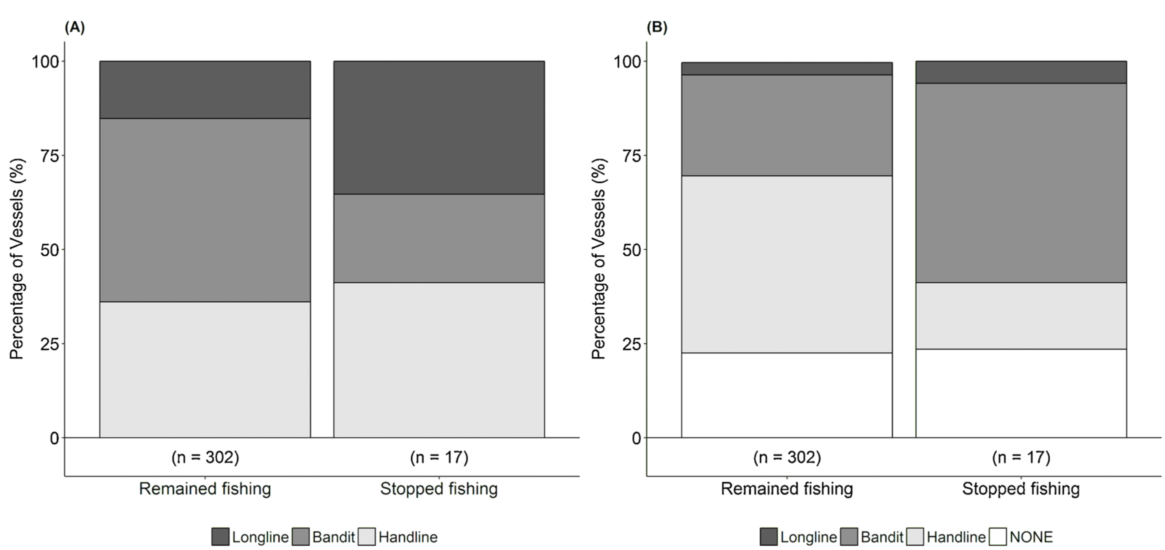

Fig. 4. Percentage of vessels used to fit the GLM that reported one of the gear types. Gear was reported as (A) the primary 'top gear' across all pre-closure logbook trips, and (B) the secondary 'top gear' across all pre-closure logbook trips (white = none). Primary and secondary gear types were calculated as a percentage from the reported 'top gear' across all pre-closure logbook trips for an individual vessel.

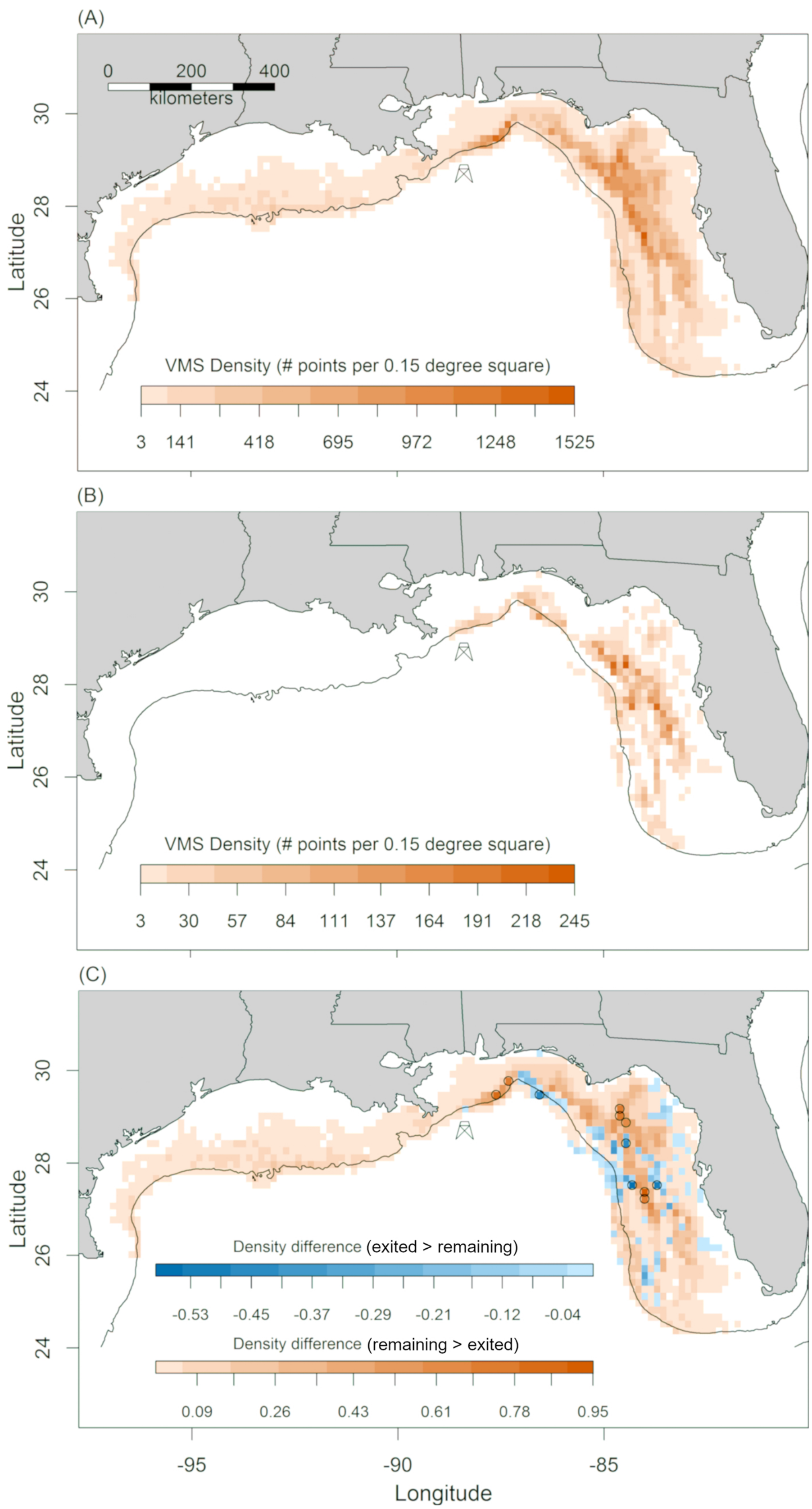

Fig. 5. Pre-closure relative effort density. (A) vessels that remained, (B) vessels that exited, and (C) the difference in relative effort density (scaled 0–1) between the two. The upper and lower one-third of values are marked with circles in panel C. Overall similiarity in space use was ˜45%.

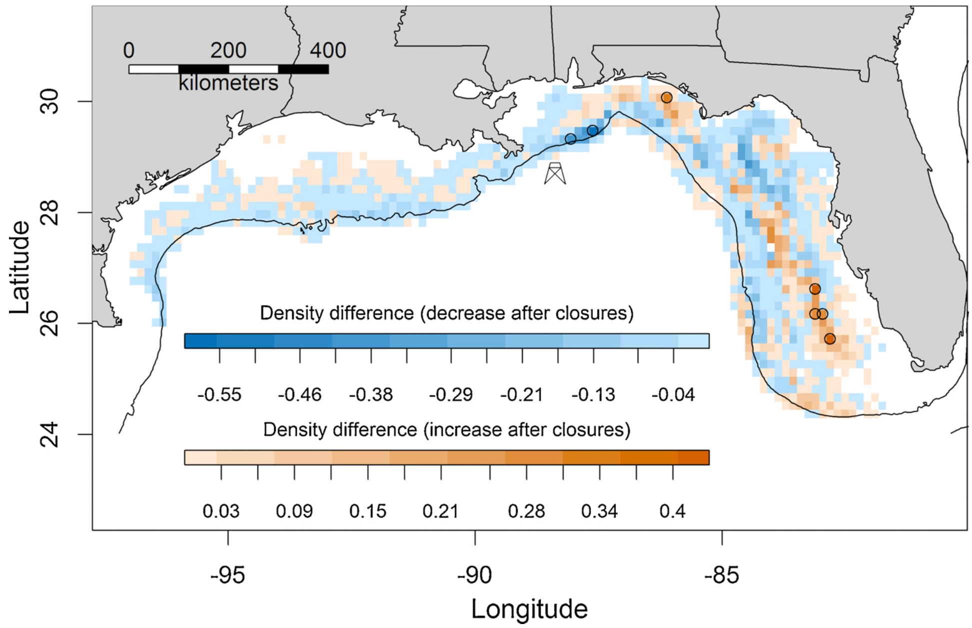

Fig. 6. Pre- to post-closure relative effort density for vessels that remained in the fishery. The upper and lower one-third of values are marked with circles. Overall similarity in space use was 80%.

offshore of the Alabama coast and Florida Panhandle and concomitant increases in effort density along the West Florida Shelf (WFS). It is possible that remaining fishers began to take advantage of an already productive fishing ground on the southern and mid-WFS during and after DWH. Characterizing and quantifying the productivity and profitability of this specific region warrants further investigation.

The model did not explicitly include spatial distribution metrics or landing state as a significant predictor of leaving the fleet. This result is somewhat surprising, given the importance of spatial dynamics in fishers' decision making and fishing outcomes (Branch et al., 2006; Dowling et al., 2012; Weninger and Perruso, 2013). Yet, pre-closure median grouper revenue was a significant predictor of exiting the fleet, and may be linked to pre-closure effort distribution. That is, catch and landings in the eastern GoM tend to contain grouper species in greater quantities than in the central or western GoM, in part due to species habitat preferences, life history strategies, and spawning locations (Koenig and Coleman, 1998; Coleman et al., 2010; Wall et al., 2011; Harter et al., 2017), the reduced size of the red snapper stock in the eastern GoM, and known distributions of the stocks (Koenig et al., 1996; Weninger and Waters, 2003; Scott-Denton et al., 2011; Zhang and Smith, 2011). The proliferation of ˜20,000 artificial reefs and ˜4000 oil and gas platforms in the western and central GoM have also established additional adult Red snapper habitat (Gallaway et al., 2009; Shipp and Bortone, 2009). The significance of grouper revenue in the model may therefore be reflecting the dominance of grouper more generally in eastern GoM trips, and the geographic disparity in distribution between vessels that exited vs. remained.

4.2. Resilience of coastal fisheries

Other studies have similarly reported on the resiliency of GoM fishes and fisheries post-DWH (Fodrie et al., 2014; Murawski et al., 2016; Schaefer et al., 2016; Peterson et al., 2017), and there is evidence that the emergency closures may have had positive effects on the abundance of some near-shore and estuarine juvenile fishes in 2010 through release of fishing mortality on spawning adults (i.e., a closure reserve effect; Fodrie and Heck, 2011; Schaefer et al., 2016). Fodrie and Heck (2011) and Schaefer et al. (2016) concluded that the oil spill did not significantly impair the community of northern GoM coastal fishes examined at the ecosystem level, and no significant post-spill shifts in community composition, structure, or biodiversity were observed. Peterson et al. (2017) similarly concluded that the DWH oil spill did not significantly impact the abundance or food-web structure of large coastal fishes in the Florida Big Bend. Population-level benefits via anomalously high recruitment and increased biomass have also been reported for Gulf menhaden (*Brevoortia patronus*) in the northern GoM (Short et al., 2017), owing to reduced predation pressure after high oil-induced mortality of some predators (i.e., seabirds, marsh birds, and bottlenose dolphins) and diversions of fresh water from the Mississippi River that inhibited access to juvenile menhaden for others. Recruitment of the 2010 Gulf menhaden year class was anomalously high and led to a population biomass that was more than twice the average biomass for the preceding decade. This population increase — especially for a major forage fish species at the base of the food web — presents the possibility of additional indirect effects throughout the northern GoM ecosystem via increased predation on Gulf menhaden prey or greater availability of Gulf menhaden biomass to surviving predators. Ultimately, the impacts of DWH will propagate through the GoM ecosystem over different time scales and with different outcomes for individual populations or systems. Economic and environmental impacts will likely be more severe and require longer recovery time for benthic fishery species such as shrimp and shellfish (Sumaila et al., 2012). For example, the spatial distribution of subtidal oyster declines from 2010 to 2012 was largely coincident with DWH oiling, freshwater diversion response activities, and subsequent salinity disruptions (Grabowski et al., 2017; Powers et al., 2017), although concomitant changes in harvesting pressure throughout the region may be confounding patterns of declines (Grabowski et al., 2017).

4.3. Changing fisher behavior

There may have been other motivations or behavioral modifications in response to these emergency closures. For instance, fishers on remaining vessels may have had the ability to use different gear types or target different species in the reef-species complex. Of the 302 vessels that remained after DWH closures, 160 (53%) used multiple gear types within single trips, 234 (78%) reported multiple top gear types between trips (see also Fig. 4), and 278 (92%) reported more than one top species group landed. The gear types used between vessels that exited and remained were slightly different (Fig. 4), and longline was reported

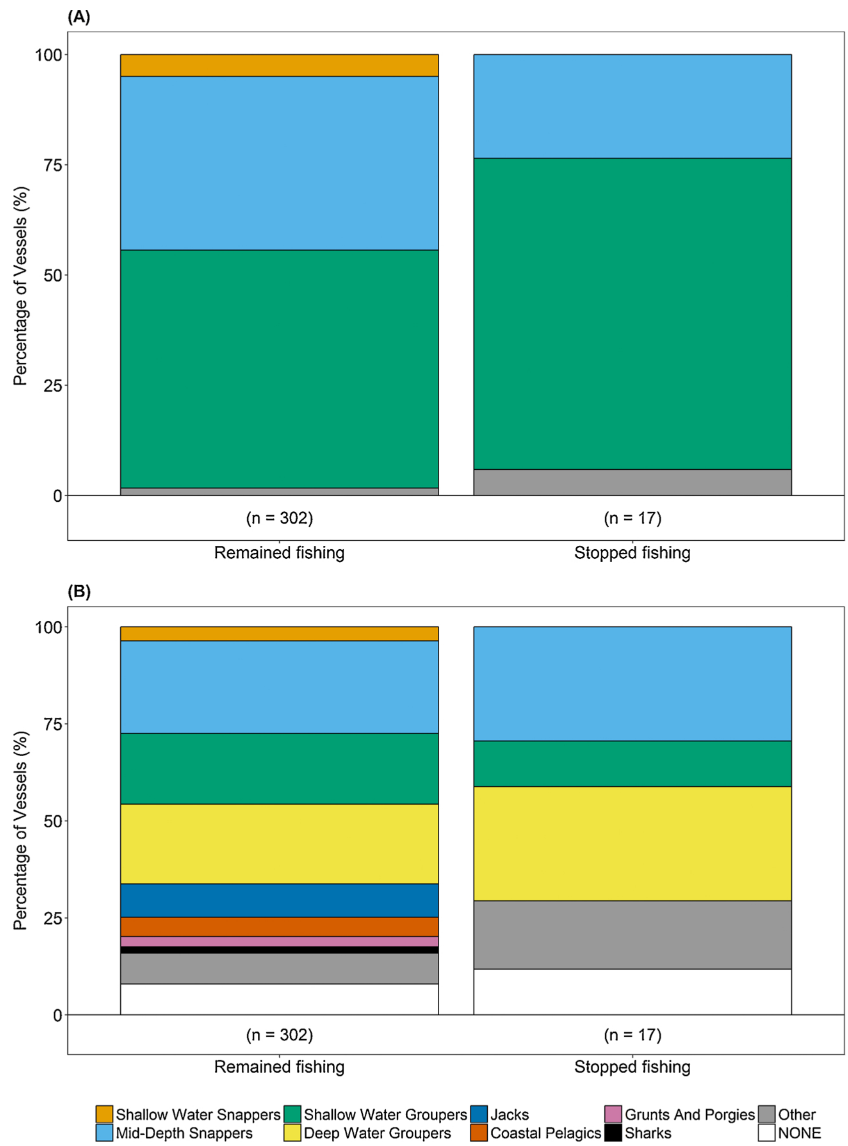

Fig. 7. Percentage of vessels used to fit the GLM that reported each of the species groups. Species was reported as (A) the primary 'top group' landed across all pre-closure logbook trips (for only the reef fish groups used in analyses; see Table 3), and (B) the secondary 'top group' landed across all pre-closure logbook trips (including landings for coastal migratory pelagics, sharks, and grunts and porgies). Primary and secondary top group landed were calculated as a percentage from the reported 'top group' across all pre-closure logbook trips for an individual vessel.

for a lesser percentage of remaining vessels. Although not significant in the GLM, the probability patterns suggest a difference between longline and vertical line gears when examining the other significant model predictors (Fig. 3). At the same time, remaining vessels had generally a richer composition of species landed (Fig. 7). It is well understood that the ability of fishers to be successful and resilient in the long term will in part depend on the diversity of the fishing portfolio. For example, Hackett et al. (2015) found that greater diversity of fishing income and lower interannual variability in fishing income were consistent predictors of remaining in a California commercial fishery after a series of regulatory changes that reduced access to fishery resources. Furthermore, Holland et al. (2017) found that the ability of U.S. fishers to diversify their income across multiple fisheries has become more constrained, especially when species are managed by catch share programs such as IFQs. These studies may support our model results, which suggest that vessels with lower grouper revenue were less likely to exit the fleet after the DWH closures (i.e., the ability to diversify operating revenues by targeting other reef fish species might allow vessels to better deal with the short-term adverse effects associated with closures). While the question of diversification is beyond the scope of this work, it is an interesting result that warrants further investigation.

4.4. Concomitant management changes

Concomitant changes in management may have also contributed to the post-DWH pattern of vessel attrition. In 2009, NMFS implemented an emergency rule for bottom longline vessels in the reef fish fishery to reduce sea turtle bycatch (NMFS, 2009). The closure lasted 164 days and prohibited bottom longlining for GoM reef fish shoreward of Cape San Blas, Florida, approximately along the 100 m (50 fathom) contour. Additionally, in May 2010, Reef Fish Amendment 31 was implemented, which includes a bottom longline endorsement program, depth and seasonal restrictions for bottom longline fishing (i.e., inside 50 fathoms east of Cape San Blas, Florida from June through August), and a limit on the number of hooks that can be possessed and fished for bottom longline gear (i.e., no more than 1000 hooks on board and no more than

750 hooks rigged for fishing at any given time).[3] In conjunction with the sea turtle emergency closure in 2009, Amendment 31 had a significant effect on the operations of the bottom longline sector. Limited-access IFQs, characterized by annual allocation privileges for each fisher, were also implemented for Red Snapper and Grouper-Tilefish species in 2007 and 2010, respectively. Amendment 31 and subsequent IFQ management are thought to have affected the composition of the Grouper-Tilefish fishery through effort rationalization. However, these effects are not well identified and difficult to measure (GMFMC, 2018; Perruso et al., 2018; Watson et al., 2018). Both IFQ programs have been shown to be successful in reducing overcapacity with reductions in the number of active vessels and increases to overall economic efficiency and productivity of the fisheries (Agar et al., 2014; Brinson and Thunberg, 2016; GMFMC, 2018; Perruso et al., 2018; Watson et al., 2018). These regulations may have therefore "primed" the fleet for increased resilience during and after the oil spill. That is, if inconsistent or marginally productive fishers left shortly before or after implementation of either Amendment 31 or the IFQs, the baseline capacity for resilience in the fleet may have been enhanced before the oil spill occurred. Explicitly teasing apart the effects of Amendment 31 on the bottom longline sector or the IFQ programs more generally from the effects of the DWH closures will require data beyond the scope of what was evaluated for this work.

4.5. Emergency compensation

Payments made through the Vessels of Opportunity (VoO) Program and to commercial fishers, crew, and vessel owners from the Seafood Compensation Program likely buffered against potential oil-related economic losses. Payments through the VoO program for spill remediation efforts totaled $283 million (paid out to 5,401 individuals), and $2.2 billion was paid out (to 5,382 individuals) through the Seafood Compensation Program for lost fishing-related income (Deepwater Horizon Claims Center, 2012). Another $6.7 billion was paid out in emergency claims (to 43,351 individuals) for general business economic losses. This is in comparison to $43.2 million in revenue from 2010 to 2014 for this fishery, and $3.8 billion in commercial revenue for all GoM key species or groups[4] over the same time period (NMFS, 2016). The financial buffer from these emergency payments likely ameliorated some of the impacts from the oil spill and subsequent fishing closures, thereby allowing more fishers to remain in the fleet than would have otherwise and decreasing the rate of vessel exit (5% compared to 14–20% background). Some fishers may have opted to leave fishing altogether in exchange for a monetary settlement, while for others the compensation payments likely provided some financial security and incentive to remain in the fleet during a very uncertain and risky period of time. A more focused analysis of the relationship between DWH emergency compensation and the decision to remain in or leave the fleet is warranted. At the time of this work, data on individual participation in the VoO program or specific compensation amounts for individual fishers were not available.

4.6. Future work

While this study is a step in understanding and modeling resilience in this fishery, it could serve as a bridge to more rigorous and data-intensive modeling of responses to sudden disturbance (e.g., oil spills or emergency rules) as well as gradual changes in spatial management (e.g., implementation of marine protected areas). Future work should focus on incorporating social and ethnographic data and finer-scale regional or community level responses, which are likely heterogeneous across space and time.

A wider range of fisher characteristics, decisions, and outcomes should be included in future modeling work, including fishers that returned to the fleet after a hiatus, moved to the recreational for-hire sector, or transitioned into working in other fishery-related or non-fishing sectors. There are a variety of social and economic drivers behind the decision to stay active in a commercial fishery; the regulatory capacity to fish is only one component of fishers' decision making. These drivers can include fishing income diversification and income stability; market channel relationships with processors, fish markets, restaurants, and others; age, health, and disability status; education level, experience, and skills that can be transferred to non-fishing sectors; other household income and employment opportunities; and the location of job opportunities outside of fishing relative to household mobility (Hackett et al., 2015). There is also likely variation among captains in the decision-making process (e.g., based on level of experience or familiarity with alternative fishing grounds) or variable decisions depending upon environmental, management, and economic conditions (e.g., weather, remaining quota for the target species, in-season species, market conditions, and profitability of fishing location) (Sanchirico and Wilen, 2001; Smith and Wilen, 2003). These data could be obtained through surveys, interviews, or workshops within fishing communities, or quantified with proxies from existing fishery data. Recent econometric work (Zhang and Smith, 2011) on the GoM reef fish fishery — using captain survey data and a similar logbook data set to that used here — revealed that travel costs, species price, captain age, and perceptions on the effectiveness of marine reserves were all drivers of fishing behavior and choice of fishing grounds after implementation of two marine reserves. Ethnographic studies to answer these types of questions would give local context and external validity to our results, and assure that our conclusions make sense for affected GoM communities (Jacob et al., 2010).

4.7. Conclusions

Given the small percentage of vessels that exited the fleet after closures, the comparatively high background rate of attrition, and the small shifts in effort distribution post-DWH, we might conclude that this commercial reef fish fleet was largely resilient to the emergency closures put in place during the DWH oil spill. Still, there is some evidence that post-DWH impacts were geographically specific, with a greater concentration of dropped vessels in the north-central and eastern GoM. While the full scope of population- and fisheries-level responses to DWH may take many years to be realized, it appears that the resilience and recovery of this fleet have been better than initially anticipated. It is important to note that the conclusion of resiliency for this particular segment of this fishery does not negate nor trivialize the loss of jobs, income, resources, property, or financial stability that resulted from the oil spill for many businesses, families, and coastal communities across the GoM.

Ultimately, understanding the factors that contribute to vulnerability, resilience, and response of fishers to regulations and disturbance will improve decision making about fisheries resources. Understanding vulnerability and resilience is equally as important for fisheries managers to identify communities that might be adversely affected by management decisions, and ensure that economic and social disruptions are minimized to the extent practicable.

CRediT authorship contribution statement

Marcy L. Cockrell: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing -

[3] See the final rule in Federal Register Vol. 75, No. 79, pp. 21512-21520 (26 April 2010) and Code of Federal Regulations Title 50 § 622.35: Gear restricted areas.

[4] Including Blue crab, Stone crab, Crawfish, Red snapper, groupers, mullets, oysters, shrimp, and tunas. Menhaden were not included in the total values reported here, since the group represents a disproportionate fraction of the commercial fishery (e.g., ˜73% of total key species landings and ˜10% of key species revenue from 2010-2014; NMFS, 2016).

original draft, Writing - review & editing, Visualization. **Shay O'Farrell:** Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing. **James Sanchirico:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Steven A. Murawski:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Larry Perruso:** Resources, Methodology, Writing - review & editing. **Andrew Strelcheck:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fishres.2019.04.017.

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