Received: 28 March 2023 | Revised: 3 August 2023 | Accepted: 7 August 2023

DOI: 10.1002/nafm.10948

ARTICLE

Evaluating bycatch avoidance in the U.S. Atlantic sea scallop *Placopecten magellanicus* fishery

Brooke A. Lowman[1] | **Catherine E. O'Keefe**[2] | **Steven X. Cadrin**[1]

[1]Department of Fisheries Oceanography, School for Marine Science and Technology, University of Massachusetts Dartmouth, New Bedford, Massachusetts, USA

[2]Fishery Applications Consulting Team, Dartmouth, Massachusetts, USA

Correspondence
Brooke A. Lowman
Email: brooke.lowman@mrc.virginia.gov

Present address
Brooke A. Lowman, Virginia Marine Resources Commission, Fisheries Management Division, Fort Monroe, Virginia, USA

Funding information
Northeast Fisheries Science Center, Grant/Award Number: NA15NMF4540063

Abstract

Objective: The effectiveness of bycatch avoidance programs relies on changes in fishing behavior in response to spatiotemporal information on bycatch patterns. A voluntary bycatch avoidance program in the U.S. sea scallop *Placopecten magellanicus* fishery designed to prevent triggering bycatch allocation of Yellowtail Flounder *Limanda ferruginea* was implemented and maintained concurrently with other management measures. Detecting bycatch avoidance behavior and relative effectiveness for bycatch mitigation presents an analytical challenge.

Methods: We evaluated effectiveness of the bycatch avoidance program over the course of 4 years based on fishing behavior relative to bycatch advisories. Using log-linear models to compare frequencies, we examined the relationship between bycatch reports from participating vessels and bycatch advisories throughout the year in each of the 4 years. We compared results from self-reported catch to data from a mandatory observer program for participating and nonparticipating vessels in the bycatch avoidance program.

Result: Significant associations between bycatch advisories and fishing locations indicated bycatch avoidance behavior, while accounting for the effect of sea scallop density on fishing location decisions. Evidence of avoidance behavior was stronger in earlier years of the program and varied spatially. Decreasing avoidance behavior coincided with revised bycatch management measures, which appear to have altered the incentives for bycatch avoidance.

Conclusion: We found differences in the fishing behavior of fishing captains who participated in the bycatch avoidance program when Yellowtail Flounder bycatch was perceived to threaten economic yield due to fishery closures. Bycatch mitigation program evaluations should consider the program objectives as well as incentives (and disincentives) in interpreting behavior.

KEYWORDS

bycatch avoidance, bycatch mitigation, fishing behavior, program evaluation, sea scallop, Yellowtail Flounder

INTRODUCTION

Bycatch, the unintentional harvest of nontargeted species or sizes, is a widespread problem facing many fisheries (Pérez Roda et al. 2019). In addition to the impact on the ecological systems in which fisheries operate, bycatch is economically problematic due to potential financial consequences of exceeding bycatch limits. The ecological and economic importance of reducing bycatch is well documented (Lewison et al. 2004, 2011; Senko et al. 2014; Komoroske and Lewison 2015; Clay et al. 2019). In practice, reducing bycatch is complicated by the economic consequences of management (e.g., forgone profit from the targeted species due to early fishery closures when a bycatch quota is exceeded). In light of the need to address both ecological and economic consequences of bycatch, a wide range of mitigation techniques have been applied, including modifications to fishing gear, gear switching, spatial and temporal closures, bycatch quotas, and fleet communications. The appropriate approach to bycatch mitigation is context dependent (Hall and Mainprize 2005; Senko et al. 2014; Little et al. 2015), and evaluation of bycatch mitigation programs should reflect the goals and intentions of the systems in which they operate (e.g., overall reduction in bycatch versus maintaining bycatch rates at or below a particular threshold).

Evaluating the effectiveness of bycatch mitigation strategies is important to ensure that goals are achieved and to improve future applications. Bycatch mitigation program reviews have been useful to identify appropriate evaluation methods based on a range of performance criteria to meet specific conservation, economic, ecosystem, and fisheries objectives (O'Keefe et al. 2014; Senko et al. 2014; Hall et al. 2017). Examining the effectiveness of specific tools, such as gear modifications and time or area closures, may be facilitated through experimental trials or impact evaluation (Hobday and Hartmann 2006; Gilman et al. 2007; Catchpole and Gray 2010; Bethoney et al. 2017; Gilman et al. 2019). Evaluations are often based on comparisons of target species catch rates to bycatch rates and amounts over time (i.e., before and after implementation of mitigation practices) and between groups of harvesters (i.e., those who do or do not participate; Senko et al. 2014; O'Keefe et al. 2014; Little et al. 2015; Bethoney et al. 2017; Somers et al. 2018). At a minimum, data on bycatch amounts and bycatch mitigation technique (e.g., altering fishing location, gear, time) are required to evaluate the efficacy of a bycatch mitigation program. Models of fishing behavior and various bycatch scenarios have also been used to simulate whether proposed solutions could be effective (Eliasen and Bichel 2016; Otto et al. 2016; Hazen et al. 2018). Cox et al. (2007) evaluated bycatch mitigation strategies for marine mammals, turtles, and seabirds, concluding that successful programs involved collaboration, monitoring, and compliance through enforcement and/or incentives. They noted that monitoring is a necessity for understanding why mitigation strategies may become less effective in practice. Similarly, Senko et al. (2014) found that collaboration with harvesters is an important factor in program success as is the context of the fishery, how it interacts with the bycatch species, and the socioeconomic conditions. O'Keefe et al. (2014) evaluated case studies of bycatch mitigation measures and found that consultation with fishers can help in the design of effective bycatch mitigation programs that reduce impacts on nontarget species and impacts from displaced fishing effort while maintaining target catch.

Impact statement

This study demonstrates a method to address the analytical challenge of detecting bycatch avoidance behavior and relative effectiveness for bycatch mitigation. Consideration of program objectives and external incentives is important in the interpretation of fishing behaviors when evaluating bycatch mitigation programs.

Bycatch avoidance program evaluation may be confounded by the set of performance criteria that is assessed. Simply examining bycatch rates or magnitude before and after program implementation may not reflect effectiveness in attaining specific goals, such as maintaining a target bycatch rate or avoiding costly regulatory requirements. Comparisons of bycatch magnitude or bycatch rates among periods are influenced by changes in relative abundance of the target and bycatch species, as well as changes in fishing that are independent of bycatch management. Therefore, assessing changes in targeting and avoidance behavior may be a more useful determinant of success in bycatch avoidance programs. Measuring changes in fishing behavior requires information on where and when harvesters operate with respect to information such as recent bycatch observations or conditions associated with the occurrence of bycatch species. However, understanding fishing behavior can present challenges as well (Salas and Gaertner 2004). For example, Calderwood et al. (2021) found an apparent lack of difference in bycatch between control and experimental fishing trips due to miscommunication between scientists and captains. Siders et al. (2023) reviewed the TurtleWatch program and found that fishers continued to operate within and closer to the recommended avoidance area as interaction limits were approached. Such results demonstrate the importance of considering incentives.

We developed an objective approach to evaluating performance of a bycatch avoidance program in the Northeast U.S. Atlantic sea scallop *Placopecten* *magellanicus* fishery to mitigate bycatch of Yellowtail Flounder *Limanda ferruginea*. Management of the sea scallop fishery has included a bycatch cap of Yellowtail Flounder since the 1990s. Uncertain stock status and decreasing stock indices of Yellowtail Flounder resulted in reduced bycatch quotas that caused closures of lucrative sea scallop fishing grounds when the fishery caught their bycatch limit (New England Fishery Management Council [NEFMC] 1999, 2015). A fleet communication bycatch avoidance program was implemented in 2010 with the objective of assisting the scallop fishery to reach its full sea scallop allocation within the constraints of Yellowtail Flounder catch limits (O'Keefe and DeCelles 2013). The program was expanded each year from 2011 to 2017 to include additional areas, fleets, and flounder bycatch species. Initial evaluations of program effectiveness included fishery participation level, maintenance of target catch, and economic yield (O'Keefe and DeCelles 2013). We extended these evaluations by examining fishing behavior to determine whether the program influenced fishing location for participating vessels in two sea scallop management areas between 2011 and 2014. The analysis examined whether participating vessels had less fishing effort in locations classified as bycatch hotspots than they did in other locations and compared the results from captains' self-reported data to data collected by observers on vessels that did and did not participate in the bycatch avoidance program.

METHODS

The University of Massachusetts Dartmouth School for Marine Science and Technology (SMAST) Flatfish Bycatch Avoidance Program, which operated from 2010 to 2017, involved near-real-time communications between fishing captains and scientists. The program focused on the Limited Access Scallop Fleet, consisting of ~350 vessels with annual, spatiotemporal individual allocations of sea scallops and fleetwide allocations of flatfish bycatch. At the start of each fishing year, sea scallop vessel captains were sent maps with a reporting grid (Figure 1). Captains

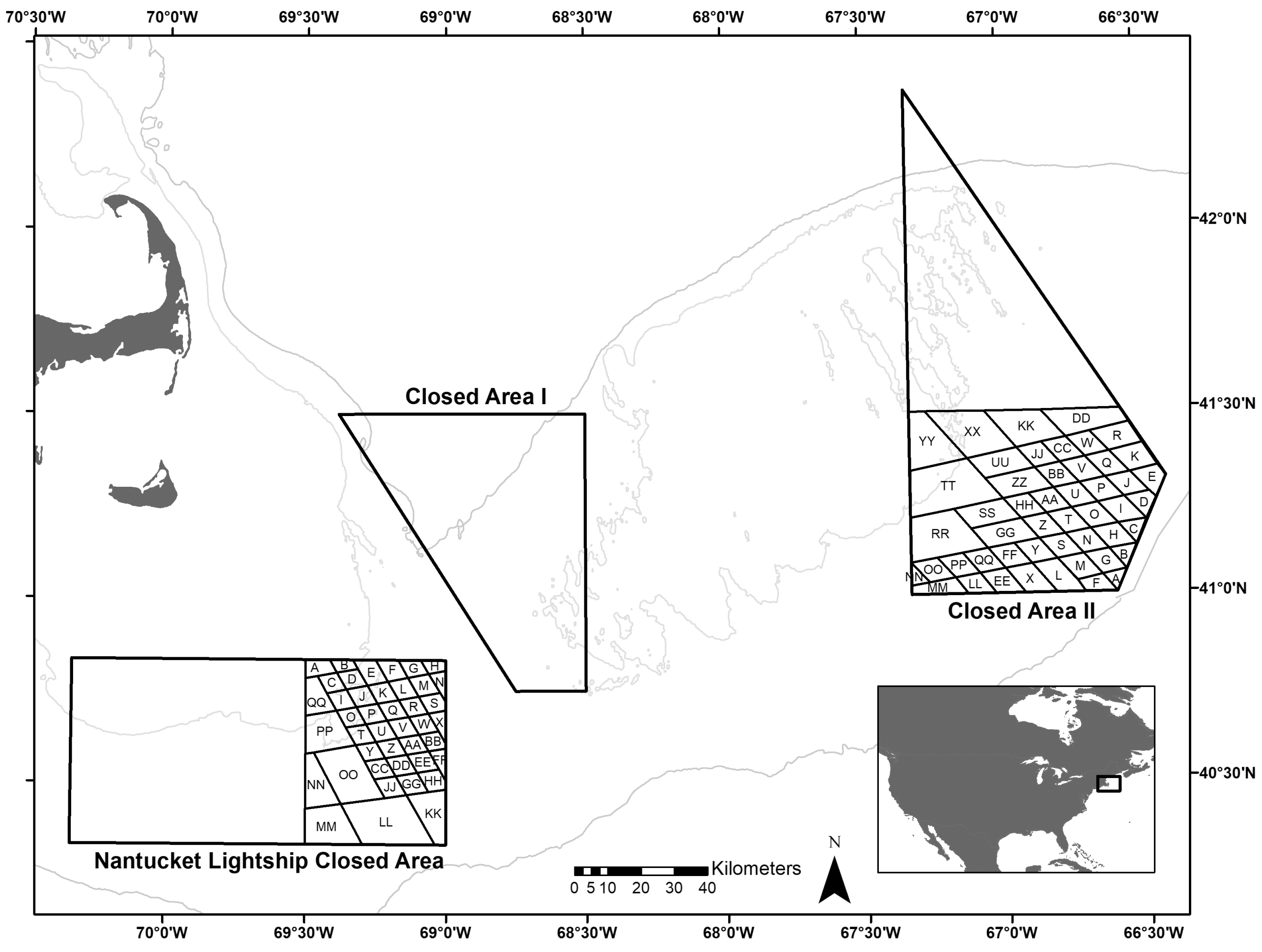

FIGURE 1 Bycatch avoidance system reporting grids in the Nantucket Lightship Closed Area and Closed Area II.

reported their daily sea scallop and Yellowtail Flounder catch (in pounds) and fishing effort (number of hauls) by grid location. Data were aggregated, and the weighted mean Yellowtail Flounder/sea scallop ratio for each grid cell was compared to predetermined bycatch threshold levels to determine the classification of "high," "medium," and "low" bycatch for advisories (further details in O'Keefe and DeCelles 2013). Thresholds were based on the annual catch allocation of sea scallops and Yellowtail Flounder to each fishing area, and classifications were assigned to individual grid cells based on fishing reports. Grid cells were assigned a "high" bycatch classification when reported bycatch ratios were above the threshold associated with exceeding the Yellowtail Flounder bycatch cap in order to land the full sea scallop allocation. Locations with intermediate or variable bycatch rates were classified as "medium" bycatch cells to alert vessels that fishing in these locations posed a risk of exceeding the Yellowtail Flounder allocation. Locations classified as "low" had bycatch rates that were expected to allow full harvest of the sea scallop target catch without exceeding the Yellowtail Flounder bycatch limit. Based on feedback from program participants, the low classification was not included in SMAST bycatch advisories after 2012.

The frequency of advisories varied throughout the duration of the bycatch avoidance program as participation changed over time. Advisories were sent to participating vessels whenever changes in bycatch hotspots were detected. At the height of the program, advisories were issued to the fleet daily. Classifications were determined for grid cells with at least three vessels fishing within a 2-week period. When there were no new vessel reports, either no advisory was sent or the most recent advisory was resent to remind vessels of the high bycatch locations. In 2011 and 2012, cell classifications remained the same in the advisories until new reports indicated a change in classification. Starting in 2013, based on feedback from program participants, the classification of a grid cell would expire after 3 weeks if no new information was reported.

We examined the relationship between bycatch reports from participating vessels ($n = 27{,}754$ dredge tows) and bycatch advisories ($n = 14{,}756$ cell advisories) for the Closed Area II (CAII) and Nantucket Lightship sea scallop access areas between 2011 and 2014 (Figure 1). Fishing reports and bycatch advisories were aggregated into time periods based on similar fishing effort (Table 1; Tables S1 and S2 in the Supplement provided in the online version of this article). The start date of the fishing season (initial date in period 1) varied by year and area as determined by management measures. Gaps between periods reflect either no fishing effort or seasonal closures imposed by management actions (e.g., seasonal closure in CAII during August and September in 2013 and 2014). Time periods were determined by analysis of the number of reported tows in each of the areas by day, and periods of higher fishing effort were defined for comparison. The time periods were selected to approximate the length of fishing trips, monthly aggregate data, or periods of similar fishing effort.

Log-linear models for frequency of advisories and reports were fit for each year in each area. Such models have been extensively applied to examine associations and patterns among categorical variables based on frequencies of observations (e.g., Agresti 2013). Our models had the following form:

$$\log\mu_{abc} = \lambda + \lambda_a + \lambda_b + \lambda_c + \lambda_{ab} + \lambda_{bc} + \lambda_{ac} + \lambda_{abc},$$

where μ_{abc} is the expected count from source a (i.e., from either the avoidance program advisories or fishing reports) in bycatch classification b (high, medium, low, or unknown) during time period c (as shown in Table 1),

TABLE 1 Time periods for each year in Closed Area II (CAII) and Nantucket Lightship Closed Area (NLCA), based on similar fishing effort.

Area	Year	Period 1	Period 2	Period 3	Period 4	Period 5	Period 6
CAII	2011	Aug 7[a]	Aug 8–Aug 12	Aug 13–Aug 25	Aug 26– Sep 2	Sep 3–Nov 30	
	2012	Jun 25–Jul 31	Aug 1–Aug 31	Sep 1– Sep 30	Oct 1– Oct 31	Nov 1– Nov 23	Nov 24–Feb 28
	2013[c]	May 30–Jun 9	Jun 11–Jun 30	Jul 1–Jul 31	Aug 1– Aug 14[b]	Nov 19–Feb 6	
	2014	Jun 19–Jul 9	Jul 10–Jul 26[c]	Jul 27–Aug 21[b]	Nov 17– Jan 20		
NLCA	2012	Jun 25–Jul 31	Aug 1–Aug 31[c]	Sep 1–Oct 31	Nov 1–Jan 11		
	2013	May 22–Aug 19	Sep 15–Dec 13	Jan 31–Feb 5[d]			
	2014[c]	Jun 18–Aug 19	Dec 5–Jan 17				

[a]Area opening defined as an individual day due to vessel aggregations in cells at area boundary.

[b]Seasonal bycatch closure late August through November 1.

[c]Excluded from analysis of observer data from nonparticipating vessels due to insufficient data.

[d]Excluded from analysis of observer data from participating vessels due to insufficient data.

and each λ is a coefficient corresponding to the sources (a), bycatch classifications (b), and time periods (c), or a combination thereof. Models that include the three-way interaction term of source, classification, and time period indicate that the interaction between source and bycatch classification changes through the fishing year (i.e., fishing behavior with respect to bycatch advisories changed over time). Loglinear model parameters were interpreted in relation to odds ratios, and only highest-order interactions were interpreted. Log odds were calculated from the model parameters by substituting them for each log(μ) in the following equation:

$$\log\theta_{ab(c)} = \log\frac{\mu_{a,b,c}\mu_{a+1,b+1,c}}{\mu_{a+1,b,c}\mu_{a,b+1,c}}.$$

To account for the effect of targeting sea scallops, we also considered the average sea scallop catch per tow (and the square of this term). The average sea scallop catch per tow was calculated among cells of the same classification within each time period. In cases when there was no available observer data for a given bycatch classification in a time period, the corresponding rows were omitted from analysis for comparisons of models with and without sea scallop terms. The three-way interaction model perfectly described the data because there was a parameter for each predicted cell frequency, so there was no information that an additional term could contribute.

Models were fit in R version 3.6.0 with the glm function (R Core Team 2019). Model selection was based on Akaike information criterion (AIC) and dissimilarity index to determine correctly classified outcomes as a measure of practical significance (Agresti 2013).

Odds ratios were also calculated directly with the model-estimated cell counts for more straightforward interpretation. For example, to compare frequencies of high- and low-bycatch advisories and reports one would consider the following ratios:

$$\frac{\text{odds high advisory}}{\text{odds low advisory}} = \frac{\text{high advisories/high reports}}{\text{low advisories/low reports}} = \frac{\text{high advisories} * \text{low reports}}{\text{low advisories} * \text{high reports}}.$$

The clearest interpretation of bycatch avoidance results is from odds ratios of high-bycatch advisories relative to low-bycatch advisories. When the log (odds ratio) was positive, the avoidance of high-bycatch cells was stronger than avoidance of low-bycatch cells. High relative to medium bycatch and medium relative to low bycatch comparisons are interpreted similarly, but we expect less difference between these classifications than between high and low bycatch. When the log(odds ratio) was approximately zero, there was neither avoidance nor preference. The bycatch ratio threshold for medium-bycatch cells was less than the Yellowtail Flounder/sea scallop ratio that would result in exceeding the Yellowtail Flounder allocation before achieving the sea scallop quota. Therefore, the expectation of avoidance behavior toward medium-bycatch cells was less clearly defined because individual fishing captains would be expected to have different attitudes toward risk taking. Comparisons involving cells with unknown bycatch levels were also evaluated, but the behavioral expectations were unclear for similar reasons.

We repeated the analysis with at-sea observer data to validate findings based on captains' reported data from the bycatch avoidance program. We received tow-level data from the Northeast Fisheries Observer Program with locations recorded as bycatch avoidance program reporting grid cells ($n = 9083$ tows). Vessels were anonymous, but an indicator was included to distinguish participants in the bycatch avoidance program from nonparticipants. Observer data from avoidance program participants were compared to captains' reported data to validate results from the avoidance program with an external data source. Results from observer data were also used to compare fishing behavior between program participants and nonparticipants.

RESULTS

Participation levels in the bycatch avoidance program varied over time, with an increasing number of vessels signed up to receive bycatch advisories but a decreasing number of vessels sending bycatch reports between 2010 and 2017 (Figure 2). Several factors influenced these conflicting trends in participation, including increased awareness to join the program and receive bycatch advisories but reduced incentives to report catch amounts due to changing bycatch management measures. The bycatch reporting rate from participating vessels fell below 20% in 2015, resulting in insufficient data for analysis; there were multiple time periods with zero advisories or reports in at least one category.

Closed area II

In CAII in 2011, the strongest evidence of avoidance behavior was from program participants in the final time period (September through November) when high- and medium-bycatch areas were significantly avoided relative to low-bycatch areas (Figure 3). There was no indication of avoidance behavior among nonparticipants in the 2011 fishing season (Figure 3). There were few high-bycatch

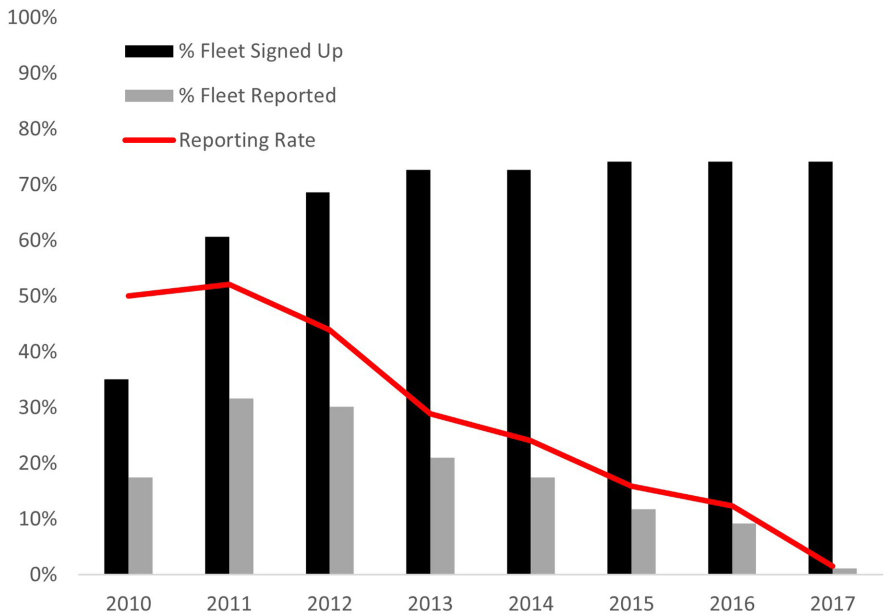

FIGURE 2 Vessel participation in the SMAST Flatfish Bycatch Avoidance Program, including the percentage of vessels in the sea scallop fleet signed up for the program to receive bycatch advisories, the percentage of the fleet that reported bycatch amounts, and the bycatch reporting rate from program participants between 2010 and 2017.

reports in the initial period (start of the fishing season on August 7), but no high reports through the remainder of periods 2–4 (Table S1), and consequently no high-bycatch advisories were issued.

In 2012, the strength of avoidance behavior in CAII varied over the course of the fishing season, with the greatest avoidance of high-bycatch areas in period 3 (September) and period 5 (November) (Figure 3). There was strong evidence of avoidance behavior by program participants in four of the six time periods, with high-bycatch areas being significantly avoided relative to medium- and low-bycatch areas (Figure 3). There was significant avoidance behavior from nonparticipants in period 2 (August), but there was a weaker indication of general avoidance behavior compared with program participants through the fishing year (Figure 3).

In 2013, due to reduced sea scallop biomass in CAII, approximately half of the sea scallop fleet (182 vessels) was allocated access under a reduced sea scallop trip limit, reducing the overall effort in the area (NEFMC 2013). Bycatch avoidance program data indicated little fishing activity in high- and medium-bycatch areas. There were no medium-bycatch advisories in the first time period (early June) and no high-bycatch reports in the first two time periods (entire month of June). There were no reports in medium-bycatch areas for the year, and no reports in high-bycatch areas in four out of five time periods (Table S1). Given the sparse bycatch avoidance program data, we could not fit reliable models for CAII in 2013 (Table S3). Program participants appear to have actively avoided bycatch because high and medium advisories were issued in periods 3 through 5 (July through November), and there were very few reports in those areas. Results from the observer data for program participants suggested no change in avoidance behavior throughout the year. High-bycatch areas were significantly avoided relative to unknown bycatch areas, and high-bycatch areas tended to be avoided relative to medium-bycatch areas (though the trend was nonsignificant; Figure 4). Almost all reports were in unknown bycatch areas. There were no data on nonparticipants in the observer data in CAII in 2013.

In CAII in 2014, high-bycatch areas were significantly avoided relative to medium bycatch in the second time period (10–26 July), and avoidance behavior declined over the rest of the year (Figure 4). There were no high-bycatch tows in the avoidance program data or in the observer data on program participants during the first time period. Nonparticipant observer data indicated that high-bycatch areas were significantly avoided relative to medium-bycatch areas (Figure 4).

Nantucket lightship

In the Nantucket Lightship Closed Area (NLCA) in 2012, there was significant avoidance of medium-bycatch areas relative to low-bycatch areas in the third and fourth time periods (September through January) (Figure 3). There were no high or medium advisories or

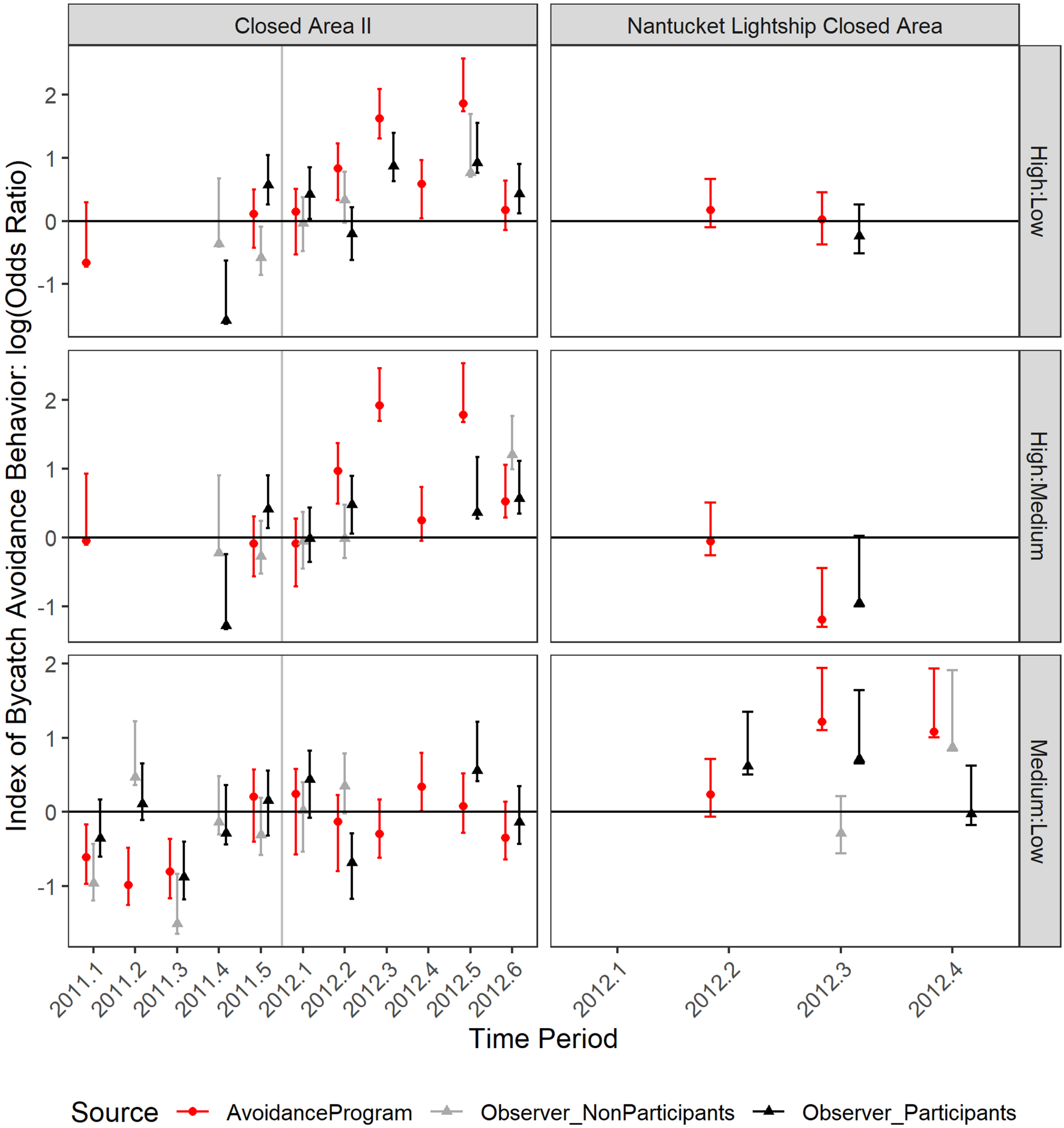

FIGURE 3 Index of bycatch avoidance behavior in 2011–2012. An index value greater than zero corresponds to bycatch avoidance behavior, and less than zero is nonavoidance behavior. Error bars are the 95% confidence interval. Time periods are as defined in Table 1.

reports in period 1, and there were no high advisories or reports in period 4 (Table S2). For the observer data on participants, there was evidence of significant avoidance behavior of high-bycatch areas relative to both low- and medium-bycatch areas. For the observer data on nonparticipants, there were no observations of fishing in high-bycatch areas.

In 2013, avoidance program data from NLCA indicated that there was significant avoidance of high-bycatch areas relative to medium areas overall (Figure 4), and there were no high or medium advisories or reports in period 3 (early February 2014). No significant avoidance behavior was seen for either observed participants or nonparticipants for high relative to medium bycatch areas.

There were only two distinct time periods in NLCA in 2014 (June–August and December–January 2015) (Table 1). In the avoidance program data, there were no high reports in the first period and no medium advisories

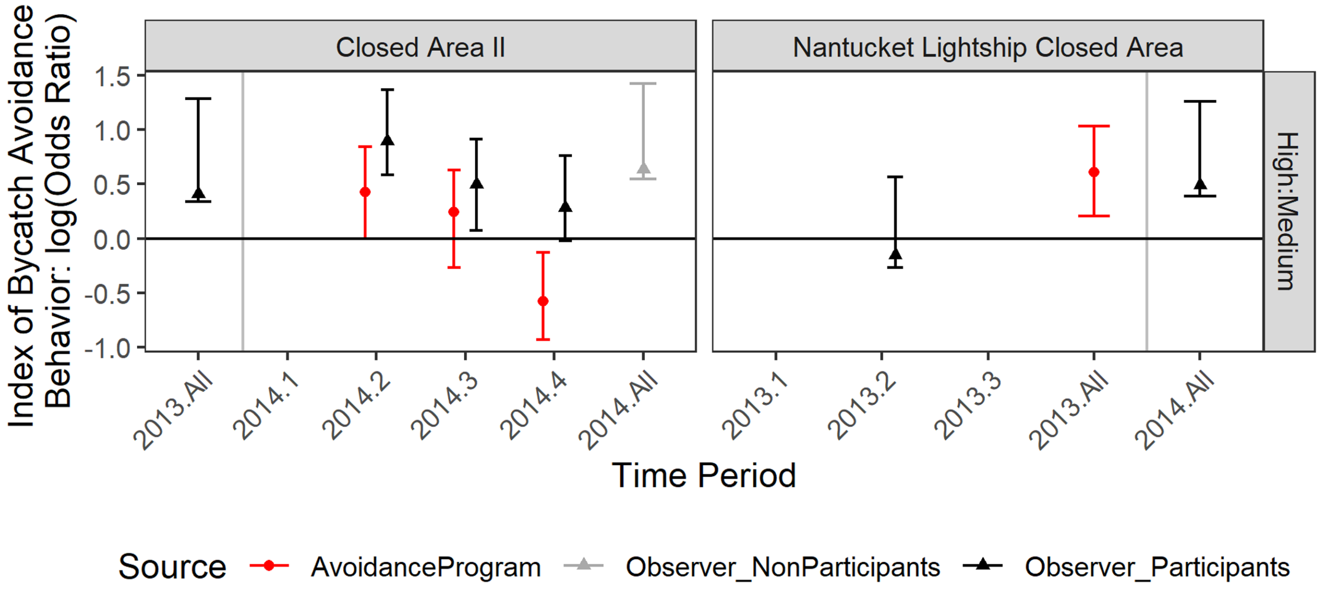

FIGURE 4 Index of bycatch avoidance behavior in 2013–2014. An index value greater than zero corresponds to bycatch avoidance behavior, and less than zero is nonavoidance behavior. Error bars are the 95% confidence interval. Time periods are as defined in Table 1. Low-bycatch areas were not listed in advisories starting in 2013; therefore, only high–medium comparisons are illustrated.

or reports in the second period. Due to the relatively large proportion of zeros in the data, we could not fit reliable models for avoidance program data in NLCA in 2014 (Table S4), and evidence of avoidance behavior is inconclusive. Although there were no high reports in period 1, there were numerous reports in medium-bycatch areas in period 1 and in high-bycatch areas in period 2 relative to the number of corresponding advisories (Table S2). Program participant observer data indicated that high-bycatch areas were avoided relative to medium-bycatch areas (Figure 4), and there were no observer data for nonparticipants.

Sea scallop density

For the avoidance program data in both CAII and NLCA, models with one interaction significantly improved with the addition of sea scallop density terms in most years. For both areas in all years, the two and three interaction models did not significantly improve according to AIC and dissimilarity index (Tables S5, S6).

For observer data from participating vessels in CAII in all years, the single interaction and simpler models improved fit by including sea scallop terms. In CAII in 2011, adding the squared mean sea scallop catch improved the model with all two-way interactions (AIC decreased substantially and correctly classified outcomes increased from 89% to 95%). In 2012–2014, the model with all two-way interactions was nominally improved (correctly classified outcomes increased by 1% or less). In NLCA the simpler models showed some improvement when adding sea scallop terms in all years, but the change in the model with all two-way interactions was very slight in 2012 and negligible in 2013 and 2014.

For the observer data from nonparticipating vessels, some of the simpler models in CAII were significantly improved and some performed more poorly when sea scallop terms were added. The model with all two-way interactions was also slightly improved in 2011 (increased from 95% to 96% correctly classified outcomes) but was not improved by adding sea scallop terms in 2012 and was negligibly improved in 2014 (<0.5% increase in correctly classified outcomes). Most NLCA models were also improved by adding sea scallop terms, though improvement of the model with all two-way interactions was negligible in both 2012 and 2013 (number of correctly classified outcomes increased by less than 0.5%).

DISCUSSION

Significant associations between bycatch advisories and fishing patterns suggest that fishing behavior was influenced by advisories and support the hypothesis that there was less fishing in high-bycatch advisory areas than would be expected if fishing location was independent of advisories. One aspect of the SMAST Flatfish Bycatch Avoidance Program that likely influenced this positive outcome was the tailoring of the program to the specific needs and operation of the fishery. The sea scallop resource has been considered healthy (and currently is not overfished and overfishing is not occurring; Northeast Fisheries Science Center 2020), while the Georges Bank Yellowtail Flounder stock status has been considered poor due to a declining biomass trend despite historically low catches (Transboundary Resources Assessment Committee 2022). The overall distribution of the sea scallop resource is relatively static through time. However, the catch rates of Yellowtail Flounder vary by season and time of day and with respect to environmental factors such as depth, bottom type, and temperature (Lowman et al. 2021).

In CAII in 2011, 2012, and 2014, the results from avoidance program data and observer data from program participants indicated significant avoidance of high-bycatch areas (especially in 2012), while results from nonparticipants' observer data indicate less avoidance behavior. Results indicate that the observed fishing behavior was not driven solely by sea scallop density. In some years, there was an interaction with time, indicating that the strength of avoidance behavior changed throughout the year. Similar avoidance behavior was observed in the NLCA in 2010, the first year of the program (O'Keefe and DeCelles 2013). This type of behavior change has also been observed in other bycatch avoidance programs. Stram and Ianelli (2014) evaluated a Chinook Salmon *Oncorhynchus tshawytscha* bycatch reduction incentive program in Alaskan Pollock *Pollachius virens* fisheries and reported that some captains shifted the timing of their fishing to avoid times of year when Chinook Salmon catch rates are known to be higher. An investigation of the efficacy of management measures in the Bering Sea–Aleutian Islands groundfish trawl fishery through analysis of fishing patterns pre- and postimplementation revealed a general shift away from fishing grounds with persistent high bycatch and an increased probability of moving at least 3 nautical miles from the end of a tow with a large amount of bycatch before resetting gear (Abbott et al. 2015). Bethoney et al. (2017) found that bycatch of river herring (Alewife *Alosa pseudoharengus* and Blueback Herring *A. aestivalis*) decreased in the U.S. Atlantic midwater trawl fishery after implementation of an avoidance program due to changes in fishing patterns. They reported an increase in the rate of reentry to locations classified as low bycatch and decreases in the rate of reentry to locations classified as moderate and high bycatch. They also reported evidence that fishing effort shifted away from highest bycatch areas in two of the three evaluation areas based on kernel density estimation of core density of fishing locations.

Results from analysis of observer data from vessels that participated in the SMAST Flatfish Bycatch Avoidance Program were consistent with results from data reported by captains to the avoidance program, validating the self-report system and supporting our conclusions about fishing behavior among harvesters in the avoidance program. Our results and previous evaluations (e.g., Roman et al. 2011; Mangi et al. 2016; Bell et al. 2017) suggest that self-reported data from harvesters can be validated with at-sea observer data to accurately represent fishery catch, bycatch, and effort.

Evidence of bycatch avoidance behavior was generally stronger in CAII than in NLCA and was stronger in the early years relative to later years. This apparent reduction in program effectiveness over time may be due to a shifting incentive structure for the sea scallop fishery. In 2011, the fishery management plan shifted from in-season closures when bycatch limits were exceeded to subsequent year closures (NEFMC 2010). In 2013, the plan included delayed implementation of fishery closures for 2 years following exceedance of bycatch limits and introduced proactive measures, including gear modifications and seasonal restrictions to minimize bycatch (NEFMC 2011, 2013). Although the number of vessels that signed up to receive bycatch advisories increased from 2011 to 2014, the number of captains sending bycatch reports decreased over the same time period. Program participants indicated that the changes in bycatch management measures reduced a “sense of urgency” for bycatch avoidance associated with in-season closures, resulting in low reporting.

Evaluations of other bycatch avoidance programs also suggest similar patterns of avoidance behavior when incentives change. For example, Abbott and Wilen (2010) concluded that bycatch of Pacific Halibut *Hippoglossus stenolepis* in Bering Sea trawl fisheries increased due to a change in targeting behavior. Original participants in the avoidance program changed their target species during the evaluation period to focus on higher-valued species associated with greater bycatch rates, whereas larger vessels that joined the program later did not change their targeting behavior. Somers et al. (2018) reported that after implementing incentives to reduce bycatch and discards through quotas in the U.S. West Coast catch share program, discard amount and proportion decreased to historic lows, discard variability decreased, and fishers expressed increased interest in gear modifications to reduce bycatch. Cox et al. (2007) documented substantial bycatch reductions in experimental demersal longline fisheries and attributed reductions to education and outreach as well as economic incentives and government responsiveness to fishers.

Although bycatch reduction is often the objective of a bycatch management program, comparisons of bycatch or bycatch rate over time or between participants and nonparticipants in a program may not be the most informative indicator of program success. Bycatch rates can be expected to decrease after the implementation of a program, and participants in the bycatch avoidance program are expected to have lower bycatch rates than their nonparticipating counterparts. However, the goal of the SMAST Flatfish Bycatch Avoidance Program was to maintain bycatch-to-target catch ratios that were no higher than the ratio which would cause a fishery closure. Maintaining such a ratio may not involve a reduction in bycatch or bycatch rate in some years because the fishery is managed in a rotational harvest strategy (NEFMC 2003), with annual variations in fishing locations and bycatch allocations. There was no incentive nor expectation for captains to reduce bycatch any further than the threshold necessary to prevent closure.

CONCLUSIONS

Although the details of a bycatch mitigation program will vary according to the context of the fishery for which it is designed (O'Keefe et al. 2014; Senko et al. 2014; Little et al. 2015; Eliasen and Bichel 2016), some guiding principles have been suggested. Bycatch program evaluations have generally concluded that clearly defined goals and objectives are critical to success (Dunn et al. 2011; Kirby and Ward 2014; Little et al. 2015), and programs are most effective when there are economic and enforcement incentives to avoid or minimize bycatch (Gilman et al. 2006; Cox et al. 2007; Dunn et al. 2011; O'Keefe et al. 2014). The objective of the SMAST Flatfish Bycatch Avoidance Program was to maintain the level of bycatch at or below the ratio which would have triggered a management response for the sea scallop fishery. Framing the objective of the program in terms of avoiding a fishery closure with resultant economic impacts rather than overall bycatch reduction provided a clear incentive for program participation. Once goals have been established, the design and implementation of programs should involve collaboration with fishers, scientists, and managers (Cox et al. 2007; Kirby and Ward 2014; O'Keefe et al. 2014; Senko et al. 2014; Gorman and Dixon 2015). From the early stages of the bycatch avoidance program, harvesters and other industry members were involved in designing protocols and were consulted throughout its duration for additional insights and feedback for improvements.

During the years that the SMAST Flatfish Bycatch Avoidance Program was operational, there were no bycatch-induced fishery closures. In this sense, the program can be viewed as successful, with the recognition that there were other concurrent changes in the fishery during these years (e.g., resource productivity, management measures). Bycatch mitigation programs based on real-time communication, such as this one, can be improved through incorporation of model predictions of bycatch in space and time. Statistical models can identify conditions that are associated with bycatch events to help inform fishing decisions. This can be especially useful for fisheries that are severely restricted by bycatch limits because bycatch advisories would not necessarily require an in-season observation of a high-bycatch event. For example, Hazen et al. (2018) describe a bycatch forecasting tool, EcoCast, based on species distribution models built using boosted regression trees incorporating environmental covariates such as depth, sea surface temperature, sea surface height anomaly, and chlorophyll *a*. Scales et al. (2018) describe a method of modeling catch and bycatch in relation to oceanographic features and conclude that incorporating Lagrangian coherent structures into dynamic ocean management could help reduce bycatch. Lowman et al. (2021) developed generalized additive models of Yellowtail Flounder bycatch in the U.S. Atlantic sea scallop fishery and found significant effects of location, bottom temperature, zenith angle, month, and year.

Discerning the effectiveness of bycatch mitigation methods is complicated by the fact that they are usually applied concurrently with other measures (Suuronen and Gilman 2020). As a component of a more holistic evaluation, we demonstrated differences in the fishing behavior of captains who participated in the bycatch avoidance program during years when Yellowtail Flounder allocations were perceived to potentially cause fishery closures. The analytical tools we developed can be valuable for evaluating bycatch avoidance behavior in other mitigation programs.

ACKNOWLEDGMENTS

We gratefully acknowledge contributions to the program from Greg DeCelles, Kevin Stokesbury, Dan Georgianna, Mike Sissenwine, Nikki Jacobson, and David Pierce. We also thank Dave Rudders, Bill DuPaul, Dvora Hart, Charles Keith, Ryan Silva, and Cheryl Corbett for program assistance and appreciate the data provided by the Northeast Fisheries Observer Program. We appreciate the help of Judith Rosellon-Druker and Alex Hansell in maintaining the program and the input of Gavin Fay and Dave Bethoney on analysis and data visualization for the program evaluation. Finally, we express our gratitude to the vessel owners and captains who participated in the program. The program evaluation was supported by the Northeast Fisheries Science Center Scallop Research Set-Aside Program (grant NA15NMF4540063).

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest related to this article.

DATA AVAILABILITY STATEMENT

Aggregated Northeast Fisheries Observer Program data are publicly available. More information is available at fisheries.noaa.gov/inport/item/24111. The SMAST Flatfish Bycatch Avoidance Program data may be made available upon request, in an aggregated format to maintain confidentiality of commercial fishers' data.

ETHICS STATEMENT

There are no ethical guidelines that were applicable to this study.

ORCID

Brooke A. Lowman https://orcid.org/0000-0002-9301-799X
Catherine E. O'Keefe https://orcid.org/0000-0002-5667-0869
Steven X. Cadrin https://orcid.org/0000-0003-0787-677X

REFERENCES

Abbott, J. K., Haynie, A. C., & Reimer, M. N. (2015). Hidden flexibility: Institutions, incentives, and the margins of selectivity in fishing. *Land Economics*, *91*(1), 169–195. https://doi.org/10.3368/le.91.1.169

Abbott, J. K., & Wilen, J. E. (2010). Voluntary cooperation in the commons? Evaluating the sea state program with reduced form and structural models. *Land Economics*, *86*(1), 131–154. https://doi.org/10.3368/le.86.1.131

Agresti, A. (2013). *Categorical data analysis*. Wiley.

Bell, R. J., Gervelis, B., Chamberlain, G., & Hoey, J. (2017). Discard estimates from self-reported catch data: An example from the U.S. northeast shelf. *North American Journal of Fisheries Management*, *37*, 1130–1144. https://doi.org/10.1080/02755947.2017.1350219

Bethoney, N. D., Schondelmeier, B. P., Kneebone, J., & Hoffman, W. S. (2017). Bridges to best management: Effects of a voluntary bycatch avoidance program in a mid-water trawl fishery. *Marine Policy*, *83*, 172–178. https://doi.org/10.1016/j.marpol.2017.06.003

Calderwood, J., Bal, G., & Reid, D. G. (2021). Trial and error: Tactical changes in fishing behavior can help reduce discards and exposure to chokes, but scientific trials can fail to spot this. *Marine Policy*, *124*, Article 104365. https://doi.org/10.1016/j.marpol.2020.104365

Catchpole, T. L., & Gray, T. S. (2010). Reducing discards of fish at sea: A review of European pilot projects. *Journal of Environmental Management*, *91*(3), 717–723. https://doi.org/10.1016/j.jenvman.2009.09.035

Clay, T. A., Small, C., Tuck, G. N., Pardo, D., Carneiro, A. P. B., Wood, A. G., Croxall, J. P., Crossin, G. T., & Phillips, R. A. (2019). A comprehensive large-scale assessment of fisheries bycatch risk to threatened seabird populations. *Journal of Applied Ecology*, *56*(8), 1882–1893. https://doi.org/10.1111/1365-2664.13407

Cox, T. M., Lewison, R. L., Zydelis, R., Crowder, L. B., Safina, C., & Read, A. J. (2007). Comparing effectiveness of experimental and implemented bycatch reduction measures: The ideal and the real. *Conservation Biology*, *21*(5), 1155–1164. https://doi.org/10.1111/j.1523-1739.2007.00772.x

Dunn, D. C., Boustany, A. M., & Halpin, P. N. (2011). Spatio-temporal management of fisheries to reduce by-catch and increase fishing selectivity. *Fish and Fisheries*, *12*, 110–119. https://doi.org/10.1111/j.1467-2979.2010.00388.x

Eliasen, S. Q., & Bichel, N. (2016). Fishers sharing real-time information about "bad" fishing locations. A tool for quota optimization under a regime of landing obligations. *Marine Policy*, *64*, 16–23. https://doi.org/10.1016/j.marpol.2015.11.007

Gilman, E., Brothers, N., & Kobayashi, D. R. (2007). Comparison of three seabird bycatch avoidance methods in Hawaii-based pelagic longline fisheries. *Fisheries Science*, *73*, 208–210. https://doi.org/10.1111/j.1444-2906.2007.01321.x

Gilman, E., Chaloupka, M., Dagorn, L., Hall, M., Hobday, A., Musyl, M., Pitcher, T., Poisson, F., Restrep, V., & Suuronen, P. (2019). Robbing Peter to pay Paul: Replacing unintended cross-taxa conflicts with intentional tradeoffs by moving from piecemeal to integrated fisheries bycatch management. *Reviews in Fish Biology and Fisheries*, *29*, 93–123. https://doi.org/10.1007/s11160-019-09547-1

Gilman, E. L., Dalzell, P., & Martin, S. (2006). Fleet communication to abate fisheries bycatch. *Marine Policy*, *30*, 360–366. https://doi.org/10.1016/j.marpol.2005.06.003

Gorman, D., & Dixon, C. (2015). Reducing discards in a temperate prawn trawl fishery: A collaborative approach to bycatch research in South Australia. *ICES Journal of Marine Science*, *72*(9), 2609–2617. https://doi.org/10.1093/icesjms/fsv147

Hall, M., Gilman, E., Minami, H., Mituhasi, T., & Carruthers, E. (2017). Mitigating bycatch in tuna fisheries. *Reviews in Fish Biology and Fisheries*, *27*, 881–908. https://doi.org/10.1007/s11160-017-9478-x

Hall, S. J., & Mainprize, B. M. (2005). Managing by-catch and discards: How much progress are we making and how can we do better? *Fish and Fisheries*, *6*, 134–155. https://doi.org/10.1111/j.1467-2979.2005.00183.x

Hazen, E. L., Scales, K. L., Maxwell, S. M., Briscoe, D. K., Welch, H., Bograd, S. J., Bailey, H., Benson, S. R., Eguchi, T., Dewar, H., Kohin, S., Costa, D. P., Crowder, L. B., & Lewison, R. L. (2018). A dynamic ocean management tool to reduce bycatch and support sustainable fisheries. *Science Advances*, *4*(5), Article aar3001. https://doi.org/10.1126/sciadv.aar3001

Hobday, A. J., & Hartmann, K. (2006). Near real-time spatial management based on habitat predictions for a longline bycatch species. *Fisheries Management and Ecology*, *13*, 365–380. https://doi.org/10.1111/j.1365-2400.2006.00515.x

Kirby, D. S., & Ward, P. (2014). Standards for the effective management of fisheries bycatch. *Marine Policy*, *44*, 419–426. https://doi.org/10.1016/j.marpol.2013.10.008

Komoroske, L. M., & Lewison, R. L. (2015). Addressing fisheries bycatch in a changing world. *Frontiers in Marine Science*, *2*, Article 83. https://doi.org/10.3389/fmars.2015.00083

Lewison, R. L., Crowder, L. B., Read, A. J., & Freeman, S. A. (2004). Understanding impacts of fisheries bycatch on marine megafauna. *Trends in Ecology and Evolution*, *19*(11), 598–604. https://doi.org/10.1016/j.tree.2004.09.004

Lewison, R. L., Soykan, C. U., Cox, T., Peckham, H., Pilcher, N., LeBoeuf, N., McDonald, S., Moore, J., Safina, C., & Crowde, L. B. (2011). Ingredients for addressing the challenges of fisheries bycatch. *Bulletin of Marine Science*, *87*(2), 235–250. https://doi.org/10.5343/bms.2010.1062

Little, A. S., Needle, C. L., Hilborn, R., Holland, D. S., & Marshall, C. T. (2015). Real-time spatial management approaches to reduce bycatch and discards: Experiences from Europe and the United States. *Fish and Fisheries*, *16*, 576–602. https://doi.org/10.1111/faf.12080

Lowman, B. A., O'Keefe, C. E., & Cadrin, S. X. (2021). Predictive models of Yellowtail Flounder bycatch in the U.S. sea scallop fishery on Georges Bank. *Journal of Northwest Atlantic Fishery Science*, *52*, 1–18. https://doi.org/10.2960/J.v52.m723

Mangi, S. C., Smith, S., & Catchpole, T. L. (2016). Assessing the capability and willingness of skippers towards fishing industry-led data collection. *Ocean and Coastal Management*, *134*, 11–19. https://doi.org/10.1016/j.ocecoaman.2016.09.027

New England Fishery Management Council. (1999). *Framework adjustment 11 to the Atlantic sea scallop fishery management plan and framework adjustment 29 to the northeast multispecies fishery management plan*. New England Fishery Management Council.

New England Fishery Management Council. (2003). *Final amendment 10 to the Atlantic scallop fishery management plan with a supplemental environmental impact statement, regulatory impact review, and regulatory flexibility analysis*. New England Fishery Management Council.

New England Fishery Management Council. (2010). *Amendment 15 to the scallop fishery management plan, including a final environmental impact statement*. New England Fishery Management Council.

New England Fishery Management Council. (2011). *Final framework 23 to the scallop fishery management plan, including a final environmental assessment*. New England Fishery Management Council.

New England Fishery Management Council. (2013). *Framework 24 to the scallop FMP and framework 49 to the multispecies FMP, including a draft environmental assessment, an initial regulatory flexibility analysis, and stock assessment and fishery evaluation report*. New England Fishery Management Council.

New England Fishery Management Council. (2015). *Framework adjustment 53 to the northeast multispecies fishery management plan*. New England Fishery Management Council.

Northeast Fisheries Science Center. (2020). *Assessment update for Atlantic sea scallops for 2020*. https://apps-st.fisheries.noaa.gov/stocksmart?stockname=Sea%20scallop%20-%20Northwestern%20Atlantic%20Coast&stockid=10786

O'Keefe, C. E., Cadrin, S. X., & Stokesbury, K. D. E. (2014). Evaluating effectiveness of time/area closures, quotas/caps, and fleet communications to reduce fisheries bycatch. *ICES Journal of Marine Science*, *71*(5), 1286–1297. https://doi.org/10.1093/icesjms/fst063

O'Keefe, C. E., & DeCelles, G. R. (2013). Forming a partnership to avoid bycatch. *Fisheries*, *38*(10), 434–444. https://doi.org/10.1080/03632415.2013.838122

Otto, S. A., Simons, S., Stoll, J. S., & Lawson, P. (2016). Making progress on bycatch avoidance in the ocean salmon fishery using a transdisciplinary approach. *ICES Journal of Marine Science*, *73*, 2380–2394. https://doi.org/10.1093/icesjms/fsw061

Pérez Roda, M. A., Gilman, E., Huntington, T., Kennelly, S. J., Suuronen, P., Chaloupka, M., & Medley, P. (2019). *A third assessment of global marine fisheries discards* (Fisheries and Aquaculture Technical Paper No. 633). Food and Agriculture Organization of the United Nations.

R Core Team. (2019). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. http://www.R-project.org/

Roman, S., Cadrin, S. X., & Jacobson, N. (2011). Assessing the reliability of fisher self-sampling programs. *North American Journal of Fishery Management*, *31*, 165–175. https://doi.org/10.1080/02755947.2011.562798

Salas, S., & Gaertner, D. (2004). The behavioural dynamics of fishers: Management implications. *Fish and Fisheries*, *5*, 153–167. https://doi.org/10.1111/j.1467-2979.2004.00146.x

Scales, K. L., Hazen, E. L., Jacox, M. G., Castruccio, F., Maxwell, S. M., Lewison, R. L., & Bograd, S. J. (2018). Fisheries bycatch risk to marine megafauna is intensified in Lagrangian coherent structures. *Proceedings of the National Academy of Sciences of the USA*, *115*(28), 7362–7367. https://doi.org/10.1073/pnas.1801270115

Senko, J., White, E. R., Heppell, S. S., & Gerber, L. R. (2014). Comparing bycatch mitigation strategies for vulnerable marine megafauna. *Animal Conservation*, *17*, 5–18. https://doi.org/10.1111/acv.12051

Siders, Z. A., Ahrens, R. N. M., Martin, S., Camp, E. V., Gaos, A. R., Wang, J. H., Marchetti, J., & Jones, T. T. (2023). Evaluation of a long-term information tool reveals continued suitability for identifying bycatch hotspots but little effect on fisher location choice. *Biological Conservation*, *279*, Article 109912. https://doi.org/10.1016/j.biocon.2023.109912

Somers, K. A., Pfeiffer, L., Miller, S., & Morrison, W. (2018). Using incentives to reduce bycatch and discarding: Results under the west coast catch share program. *Coastal Management*, *46*(6), 621–637. https://doi.org/10.1080/08920753.2018.1522492

Stram, D. L., & Ianelli, J. N. (2014). Evaluating the efficacy of salmon bycatch measures using fishery-dependent data. *ICES Journal of Marine Science*, *72*(4), 1173–1180. https://doi.org/10.1093/icesjms/fsu168

Suuronen, P., & Gilman, E. (2020). Monitoring and managing fisheries discards: New technologies and approaches. *Marine Policy*, *116*, Article 103554. https://doi.org/10.1016/j.marpol.2019.103554

Transboundary Resources Assessment Committee. (2022). *Georges Bank Yellowtail Flounder* (TRAC Status Report 2022/01). Transboundary Resources Assessment Committee.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.