Inter-Research Science Publisher

Marine Ecology Progress Series
Volume 756:51–69

Published March 13, 2025
https://doi.org/10.3354/meps14806

OPEN ACCESS

Effect of trap soak times on risk of bycatch from offshore lobster *Homarus americanus* fishing operations in southwest Nova Scotia, Canada

Raphael Vanderstichel[1,4,*], Catherine Boyd[2], Adam Delargy[3], Craig Lego[3], James Mosher[2], Christine Penney[2], Matt Sarty[2], Kevin Stokesbury[3]

[1]College of Veterinary Medicine, Long Island University, Brookville, NY 11548, USA
[2]Clearwater Seafoods LP, Bedford, Nova Scotia B4A 3Z7, Canada
[3]Department of Fisheries Oceanography, University of Massachusetts, Dartmouth, MA 02747, USA

[4]*Present address:* Department of Veterinary Sciences, University of Wyoming, Laramie, WY 82071, USA

ABSTRACT: The Canadian lobster *Homarus americanus* industry faces the challenge of minimizing bycatch (discarded lobster and non-target species) while optimizing catch rates in a quota-managed fishery. This study assessed the effect of varying soak times (2–14 d) on trap catches off the southwest coast of Nova Scotia. In a 1 yr, controlled, industry-led trial, the most comprehensive study of bycatch in the Canadian lobster industry, soak times were representative of commercial operations, and electronic monitoring provided independently validated data. Employing mixed logistic regressions, a significant correlation was found between extended soak times and increased risk of capturing cusk *Brosme brosme* and unidentified bycatch species (not specifically monitored), while no significant associations were observed for white hake *Urophycis tenuis*, Jonah crab *Cancer borealis*, Atlantic cod *Gadus morhua*, and rock crab *Cancer irroratus*. The overall impact of soak times on estimated bycatch weights for cusk and unidentified species was minor compared to more influential factors such as fishing area, depth, and temporal trends. Reducing soak times may decrease cusk and unidentified bycatch but would lead to a substantial reduction in landed lobster, requiring increased fishing efforts. Historical evidence, from regular independent at-sea observer coverage and government analysis, emphasizes that fleet rationalization and footprint concentration through trap reduction exerted a larger impact on bycatch rates than the observed changes from soak time alterations in the study. Acknowledging such historical insights will be helpful for planning strategies for mitigating bycatch in lobster trap fisheries taking place in similar environmental and operational conditions.

KEY WORDS: *Homarus americanus* · Lobster · Bycatch · Trap haul · Gear · Soak time · Electronic monitoring

1. INTRODUCTION

Lobster *Homarus americanus* fishing area (LFA) 41 in the Canadian offshore was established in 1972, encompassing an area 50 nautical miles (92 km) from shore to the upper continental slope off the southwest coast of Nova Scotia (DFO 2000; see Fig. 1). Like all commercial fishing activities in Canada, the fishery in LFA 41 is federally regulated by Fisheries and Oceans Canada (DFO). Operated year-round, the primary lobster catch occurs between November and July, with reduced fishing activity from August to October due to the prevalence of soft-shelled lobsters in the population, which are deemed less suitable for markets (Thakur et al. 2017). Lobsters are crustaceans that molt periodically to grow, shedding their exoskeleton and forming a new, softer shell. Baited traps, organized in strings of 100 traps each, are deployed

*Corresponding author: rvander4@uwyo.edu

Publisher: Inter-Research · www.int-res.com

along the seafloor (referred to as 'strings' or 'trawls'), with buoy lines marking each end. The fishery in LFA 41, conducted by one vessel since 2012 (operated by Clearwater Seafoods), deploys between 43 and 55 strings, varying seasonally, and adheres to an annual total allowable catch (TAC) of 720 tonnes (t) of lobsters (also referred to as landed lobsters; DFO 2018, 2023).

The fishery is permitted to retain only those lobsters at or above the minimum legal size (carapace length: 82.5 mm) and there are prohibitions on the retention of egg-bearing or 'berried' females and V-notched females (lobsters that have been previously captured, identified as breeding females by a V-shaped notch cut into a tail flipper, and released) regardless of their size (Pezzack et al. 2015, DFO 2023). There exists a potential for incidental capture of non-target species, commonly referred to as bycatch. All prohibited lobster and non-target species are required to be released at sea. Notable bycatch species in LFA 41 include (in descending order by hauled weight): lobster (undersized, V-notched, and berried females), Jonah crab *Cancer borealis*, cusk *Brosme brosme*, hake (red: *Urophycis chuss*; white: *U. tenuis*), Atlantic cod *Gadus morhua*, rock crab *C. irroratus*, and redfish *Sebastes mentella* and *S. fasciatus* (Pezzack et al. 2015, Cook et al. 2017, DFO 2018, 2023). Of these, cusk and Atlantic cod are of management interest due to their depressed stock status (Pezzack et al. 2015). The average annual non-lobster bycatch between 2018 and 2022 was estimated at 31.2 t, constituting approximately 4% of the total lobster landings (DFO 2023) in LFA 41. Although released invertebrates are assumed to have a high survival rate, finfish species may experience lower survival rates due to expansion of swim bladders when hauled (DFO 2008, Pezzack et al. 2009, Cook et al. 2017). Notably, there has been a substantive decline in offshore bycatch from 2006 to 2015 (from 126 to 19 t), attributed to a rationalization of the fleet (fewer vessels and traps used to catch the same TAC) and an increased focus on areas with the highest lobster catch per unit effort (Cook et al. 2017).

Canada mandates that all commercial fixed gear must be tended within 72 h, a regulation currently under review (DFO Forward Regulatory Plan; https://www.dfo-mpo.gc.ca/acts-lois/initiatives/rule-reglement-eng.htm#reg05). Soak times may extend due to adverse weather conditions, vessel breakdowns, maintenance, or other unforeseen circumstances. DFO has highlighted the importance of understanding bycatch given the potential negative impacts of trap fisheries on non-target species, as capturing these species could constitute unmanaged mortality and, in some circumstances, disrupt ecosystem balances (Pezzack et al. 2014). Therefore, understanding the environmental consequences of different trap soak times on various bycatch species could enhance trap fishery management.

Limited information exists on the influence of soak time on bycatch species in *H. americanus* trap fisheries. Studies by Boenish & Chen (2018) and Sweezey et al. (2020) found no significant correlation between soak time and catch rates of Atlantic cod in the Gulf of Maine lobster fishery, with soak times ranging from 0–45 d and 1–7 d, respectively. Anderson et al. (2020) observed no evidence of physical trauma to sea raven *Hemitripterus americanus* and longhorn sculpin *Myoxocephalus octodecemspinosus* over a 6 d soak period in the Gulf of Maine fishery. Similarly, Boudreau & Hanley (2023) found that 98% of all bycatch species (including undersized lobsters and berried females) were undamaged after 1–2 d soak time in the southern Gulf of Saint Lawrence lobster fishery. However, these studies either focused on specific bycatch species or did not examine a range of soak times, limiting the comprehensive understanding of the impact of soak time on bycatch rates. To the knowledge of the authors, no empirical evidence is available to understand the potential effects of soak times on bycatch risk, mortality rates, and further bycatch impacts in the Canadian lobster industry.

During typical commercial fishing, soak days do not vary much in duration, unless fishing is disrupted by weather or vessel problems. To test the influence of differences in soak times, a controlled trial, rather than an observational study, would ensure an adequate representation of soak times across a wider range of possible durations and areas observed in commercial operations. All data used for analysis was collected by the crew, and electronic video monitoring on board the fishing vessel was used to ensure transparency and enable independent validation of raw data. The primary objective of this 1 yr controlled trial was to estimate the effect of soak times (ranging from 2 to 14 d) of lobster traps on the risk of catching both target species (market-size lobster) and non-target species (discarded lobster and other bycatch) off the southwest coast of Nova Scotia. This study collected the most extensive information on trap-level bycatch data to date in the Canadian lobster offshore operation for a 1 yr period, allowing for the second objective of describing and estimating current overall expected bycatch rates, and the effects of soak time on the bycatch rates, in the offshore industry (i.e. in the LFA 41 area).

2. MATERIALS AND METHODS

2.1. Study design

In the controlled trial, 4 strings were utilized, each with approximately 50 traps, deviating from the common practice of using strings with around 100 traps. This modification aimed to increase the number of strings in the study from the number of traps available. These adjusted strings were seamlessly integrated into the ongoing commercial fishing operation in LFA 41 over the data collection period spanning July 2021 to August 2022, with a continuous rotation of soak times in an effort to obtain equal representation of 4 durations: 2, 3, 7, and 14 d throughout the study. This rotation covered all 4 seasons in the 3 fishing areas (Southwest Browns Bank, Georges Basin, and Southeast Browns Bank) targeted by the fishery (Fig. 1). The determined soak time durations were chosen to represent realistic options for commercial operations. To accommodate the longer soak times in this study, a Section 52 license (commonly known as a scientific license) was issued by DFO.

Given the challenges inherent in offshore fishing operations, difficulties adhering to the exact soak time schedule were anticipated; therefore, we recorded the actual time spent at sea for each string based on their deployed and hauled time stamps. However, emphasis was placed on the crew's role in maintaining a continuous rotation of study strings with the various soak days, to the best of their ability. Additionally, with the use of adjusted strings with 50 traps for the study and considering the crew's involvement in deploying and hauling the study traps, neither the crew nor the researchers could be blinded to the soak times in the study. When the study traps were retrieved after the prescribed soak durations, crew members identified the catch, which comprised the data set used in all analyses. Ensuring accurate counts of animals in the study traps was paramount; therefore, the operations were electronically monitored (video-captured) to facilitate independent evaluations of bycatch counts and spe-

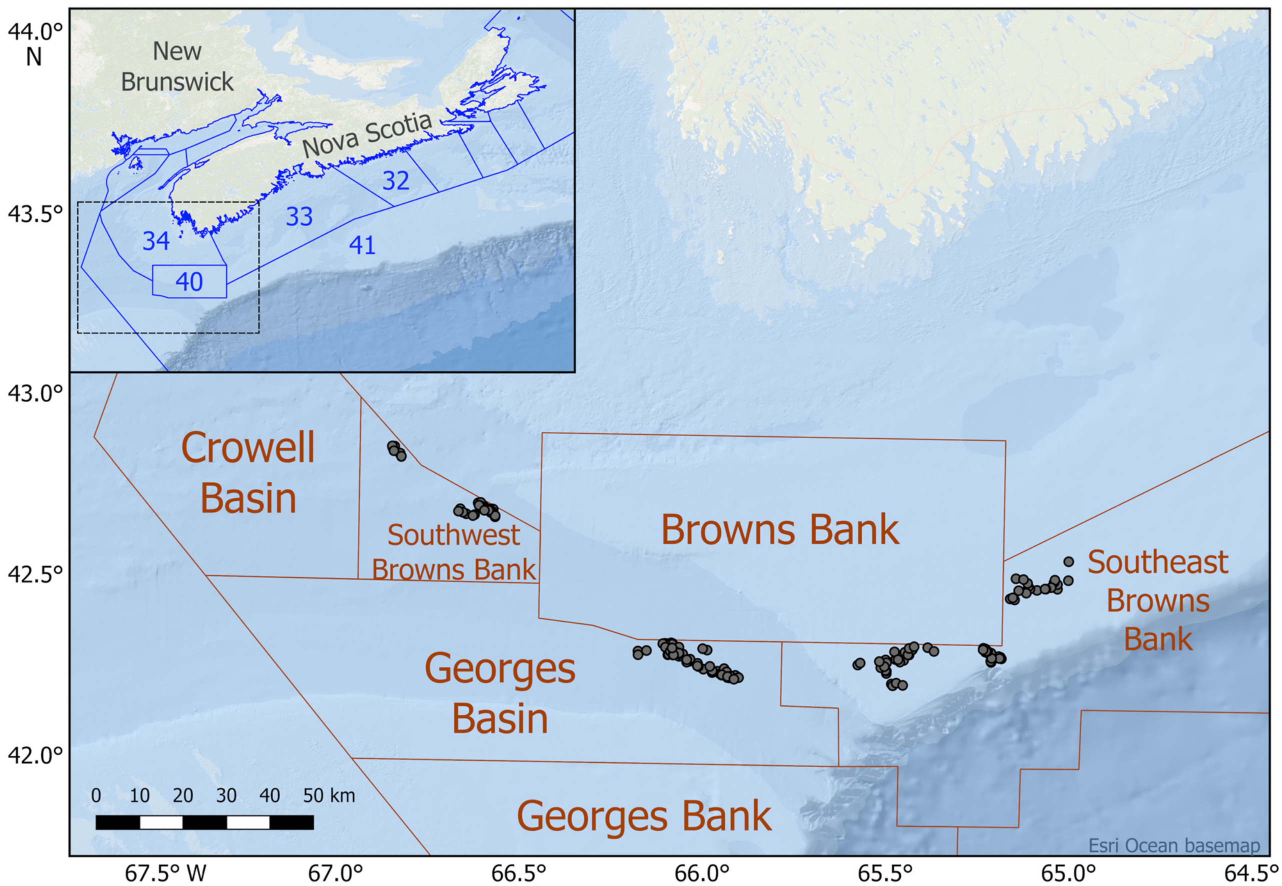

Fig. 1. Offshore string locations southwest of Nova Scotia in Lobster Fishing Area 41, further divided into 3 fishing areas: Southwest Browns Bank, Georges Basin, and Southeast Browns Bank

cies agreement between video analysis and crew-recorded data.

The crew recorded both string-level and trap-level information. String-level data included trip identification, set date, hauled date, calculated soak time (in decimal days), and location (latitude, longitude) for the start and end of the string. The trap-level data included unique identifiers for the trip, string, and trap, hauled date, and species-specific information (number and estimated weight from sight and feel, in lbs) for marketable lobster (kept), discarded (live) lobster, dead lobster, pieces of lobster, cusk, Atlantic cod, white hake, rock crab, and Jonah crab. All other species were categorized as unidentified species based on predicted low catch rates or other bycatch species that would prevent sufficient power for statistical evaluation (DFO 2020, 2023). Previous observations on the bycatch composition of this fishery indicated that species other than the 6 specifically listed here would be encountered very infrequently and in small amounts (DFO 2023). To minimize the extra burden on the crew, they were instructed to categorize all other species as unidentified. This decision was based on the authors' confidence that these species would not appear in sufficient numbers to generate statistically significant data on the effects of soak times.

Depth information at string locations (recorded at the start of each string) was extracted from DFO bathymetry data (A. Cook pers. comm.) using the 'raster' package (Hijmans 2023) in the R statistical programming language (R Core Team 2022). Counts and weights of animals (separate for dead and alive) were aggregated within each trap, and risk was defined as the probability of a bycatch animal being present in a trap.

2.2. Electronic monitoring

To validate confidence in crew-reported data and as a condition of the Section 52 license, all strings in the study were electronically captured by video cameras (IP Camera; model no. IPC4531CA-28), which were strategically placed in 3 locations on the vessel to ensure chain of custody. The operations were recorded at the side of the vessel where traps were hauled aboard, into the below-deck working area, and above the discard chute. Video reviewers had a clear view of traps during retrieval, harvesters sorting catch, and the discarding process. Lobsters were classified as dead or alive based on their behavior when handled by the fishers. Dead lobsters appeared limp when lifted, while live lobsters exhibited movement, particularly in the legs and tail. A subset of the video recordings underwent an independent evaluation of bycatch counts by human technicians trained in species identification. The Tator image platform (https://www.tator.io), developed by CVision AI, played a pivotal role in this process, providing a streamlined workflow for uploading, storing, annotating, and verifying videos.

To ensure the reliability of video evaluations, trap-level counts from each assessed string were independently conducted in duplicate (with blinding) and subsequently paired with crew trap counts on board the vessel. Since not all study strings could undergo independent evaluation, preliminary analyses on the first 10 strings in the study demonstrated that adequate precision was achieved. This assurance prompted the expansion of the study to audit 10 strings per quarter, randomly and blindly selected by the technicians, culminating in a representative sample of 40 strings out of 154 for the entire study duration.

Agreement analyses involved the generation of a contingency table with trap counts for each bycatch species from matched video and crew counts, presenting results on an ordinal scale. To evaluate agreement, Cohen's kappa (with linear weights) was calculated from count frequencies for each contingency table (Choudhary & Nagaraja 2017), while the marginal homogeneity (MH; Stuart-Maxwell) test was used to assess symmetry. This aimed to determine if systematic differences were observed between the video and crew counts (Stuart 1955, Maxwell 1970). The visualization of agreements between video and crew counts for each bycatch species was facilitated by Bangdiwala's agreement chart (Bangdiwala 2017), generated using the 'vcd' package (Meyer et al. 2023) in R (R Core Team 2022). Data generated from electronic monitoring were only used for the agreement analyses and were not used in any way to modify the original crew-recorded data in this study.

2.3. Statistical analyses

Mixed logistic regression models were employed to assess bycatch risk, treating each bycatch species as a dichotomous trap-level outcome (0 or 1) indicating the absence or presence of an animal in a trap. To account for expected similarities within strings, string was incorporated as a random effect (u_j), establishing a 2-level hierarchical structure in all models. The soak time variable was included as a fixed effect in all models (S_{ij}), while the remaining variables were added as fixed effects to control for potential confounding factors, namely, the spatiotemporal characteristics (date T_{ij}, fishing area [dummy variables for Georges Basin and Southeast Browns Bank; F_{1ij} and F_{2ij}], and depth D_{ij}), and whether live lobster(s) were present in the trap (L_{ij}); the estimated main effect of soak day would otherwise potentially be distorted if these confounding effects were omitted from the models. Additionally, a string-level contextual effect (C_{ij}) was introduced, summarizing the average number of live lobsters per trap on a string, which was a proxy measure for lobster density in the immediate fishing location. The model equation was:

$$\text{logit}(P(Y_{ij} = 1)) = \beta_0+\beta_1 S_{ij}+\beta_2 T_{ij}+\beta_3 F_{1ij}+\beta_4 F_{2ij}+ \beta_5 D_{ij}+\beta_6 L_{ij}+\beta_7 C_{ij}+u_j$$

where Y_{ij} is the dichotomous outcome indicating the presence (1) or absence (0) of an animal in the trap for the ith trap in the jth string and u_j is the random effect for the jth string, assumed to follow a normal distribution with mean 0 and variance σ_u^2 ($u_j \sim N(0,\sigma_u^2)$).

Stepwise backward procedures were employed in the model-building process to eliminate non-significant variables, with a significance level set at $p < 0.05$. Model diagnostics involved inspecting string-level best linear unbiased predictions and trap-level residuals for homoscedasticity and normality. Fractional polynomials (restricted to single terms) were used to address non-linear relationships between predictors and outcomes. Likelihood ratio tests (LRTs) were used to determine the significance of soak times in the final models, while Wald tests were applied for the remaining variables throughout the model-building process (Dohoo et al. 2009).

2.4. Power analyses

Preliminary sample size calculations for the number of traps needed were based on mean animal weights and standard deviations recorded between 2002 and 2016. These data, obtained through a data access request from DFO, were collected during independently observed commercial fishing trips (i.e. independent at-sea observed trips). Preliminary estimates suggested that approximately 800 traps per comparison group (with 50 traps per string) would be sufficient to detect a change in mean difference of at least 1.76 kg for Jonah crab (α = 0.05, power = 0.90), and even smaller differences for cusk (0.69 kg), Atlantic cod (0.50 kg), white hake (0.50 kg), and rock crab (0.17 kg). Given the uncertainty in these estimates, sample size calculations were re-evaluated based on empirical data collected in the first 6 mo of sampling.

These updated calculations, performed with the 'lme4' and 'simr' packages in R (Bates et al. 2015, Green & McLeod 2016), considered the hierarchical structure of the data (50 traps nested within strings) and provided improved power estimates through simulated data (1000 iterations) extending mixed logistic regression model estimates.

2.5. Predictions for fishing in LFA 41

Predictions for total bycatch in LFA 41 were based on the study string estimates extrapolated to the regional commercial operations in LFA 41 during the study period. For each commercially deployed string, locations, soak times, number of traps, and total market-sized lobster weights were recorded. Fishing areas and depths were extracted for each string location, and the average soak time, date, depth, and average number of lobsters per trap along with the proportions of strings in each fishing area were used as explanatory variables in mixed logistic regression models for each bycatch species. Model predictions were reported as probabilities for traps to have at least one bycatch species. These probabilities were then multiplied by the total number of traps from the commercial operation and the observed averages of bycatch weight per trap (with at least one relevant bycatch animal) from the study (kg). Estimated effects of soak times were also extrapolated to the whole LFA 41 fishing area using the same calculation methods.

Unless stated otherwise, all statistical analyses were conducted in Stata (v.17) (StataCorp 2022). Maps were generated in QGIS (QGIS Development Team 2022), utilizing ESRI'S Ocean basemap (ESRI 2022), and image handling was performed in GIMP (GIMP Development Team 2022).

3. RESULTS

Between July 2021 and August 2022, 40 offshore trips were recorded, deploying study strings for a total of 154 times (Fig. 1). Each string had between 43 and 52 traps, with the majority having exactly 50 traps (mean: 49.83; median: 50), resulting in 7674 trap hauls during the study period (Table 1). The most common bycatch species, in decreasing total weight, were white hake (988.9 kg, n = 1323), Jonah crab (386.7 kg, n = 889), cusk (330.5 kg, n = 203), Atlantic cod (270.2 kg, n = 144), unidentified (249.8 kg, n = 342),

Table 1. Summary statistics for bycatch species for the entire study (n = 154 strings, each with approximately 50 traps). Data are averaged by trap (n = 7674) and specifically focused on traps with at least one bycatch animal present, including a subset of dead animals (from the total reported above), and piece(s) of lobster

	Overall		Average trap^{-1}		≥1 animal in a trap					
	Weight (kg)	Count	Weight (kg)	Count	% Traps	Mean weight (kg)	Mean count	Min. count	Median count	Max. count
White hake	988.9	1323	0.1289	0.172	11.52	1.119	1.497	1	1	9
Dead	81.6	90	0.0106	0.012	1.12	0.949	1.047	1	1	2
Cusk	330.5	203	0.0431	0.026	2.46	1.748	1.074	1	1	3
Dead	55.0	38	0.0072	0.005	0.48	1.486	1.027	1	1	2
Jonah crab	386.7	889	0.0504	0.116	7.99	0.631	1.450	1	1	10
Dead	2.7	4	0.0004	<0.001	0.05	0.682	1.000	1	1	1
Atlantic cod	270.2	144	0.0352	0.019	1.76	2.002	1.067	1	1	3
Dead	22.0	18	0.0029	0.002	0.22	1.300	1.059	1	1	2
Unidentified	249.8	342	0.0326	0.045	4.31	0.754	1.033	1	1	2
Dead	38.0	55	0.0049	0.007	0.69	0.716	1.038	1	1	2
Rock crab	30.5	118	0.0040	0.015	1.04	0.381	1.475	1	1	5
Dead	1.4	3	0.0002	<0.001	0.04	0.455	1.000	1	1	1
Lobster										
Kept	22883.5	24036	2.9820	3.132	80.52	3.703	3.890	1	3	21
Discarded	7501.4	7986	0.9775	1.041	51.49	1.899	2.021	1	2	14
Dead	245.6	267	0.0320	0.035	2.54	1.260	1.369	1	1	7
Piece(s)	–	1875	–	0.244	10.35	–	2.361	1	2	18

and rock crab (30.5 kg, n = 118) (Table 1). There were 1902 traps with at least one non-lobster bycatch, representing 24.8% of all trap hauls in the study. During this period, there were 24 036 landed lobsters (5899.7 kg), and 7986 discarded lobsters (7719 alive, 267 dead; total weight: 3887.2 kg); 80.5% of traps had at least one market-sized lobster, while 51.5% had lobsters that were returned (discarded) and overall, 86.4% of traps had live lobsters (either kept and/or discarded).

3.1. Electronic monitoring

The reliability of trap bycatch counts from electronically captured records was independently assessed on 40 strings, comprising 10 strings randomly selected per quarter. This evaluation provided a robust basis for gauging the agreement between crew counts and electronic records for more than 25% of the strings in the study. Adhering to the established guidelines for interpreting kappa values, as defined by Landis & Koch (1977), the results indicated almost perfect agreement for landed lobsters (0.91), discarded lobsters (0.85), and Jonah crab (0.82). Substantial agreement was observed for lobster pieces (0.74), hake (0.73), cusk (0.71), and Atlantic cod (0.70), while fair agreement characterized dead lobsters (0.50) and unidentified species (0.45). However, no agreement was noted for rock crab (0.00) (Fig. 2).

The assessment of symmetry, conducted through the MH test and Bangdiwala's agreement chart, revealed several findings. Higher crew counts, denoted by rectangles extending above diagonal lines in Fig. 2, were identified for discarded lobsters (MH, $p = 0.005$), hake (MH, $p = 0.024$), and cusk (MH, $p = 0.006$). Conversely, higher video counts, illustrated by rectangles extending below diagonal lines in Fig. 2, were evident for dead lobsters (MH, $p < 0.001$), lobster pieces (MH, $p = 0.002$), and unidentified species (MH, $p < 0.001$). No differences in symmetry were observed for landed lobsters (MH, $p = 0.126$), Jonah crab (MH, $p = 0.103$), Atlantic cod (MH, $p = 0.513$), and rock crab (MH, $p = 0.368$). The agreement analyses support the use of crew-reported data for all subsequent analyses.

3.2. Impact of soak times

String soak times ranged from 0.5 to 22.8 d (2.5th and 97.5th percentiles: 1.7 and 16.0 d, respectively), with a mean and median of 7.98 and 7.79 d, respectively (Fig. 3). Soak times were distributed across 3 fishing areas (Southwest Browns Bank, Georges Basin, and Southeast Browns Bank) and evenly throughout the year, except for a 2 mo gap in September and October 2021 when no commercial fishing occurred due to high proportions of soft-shelled

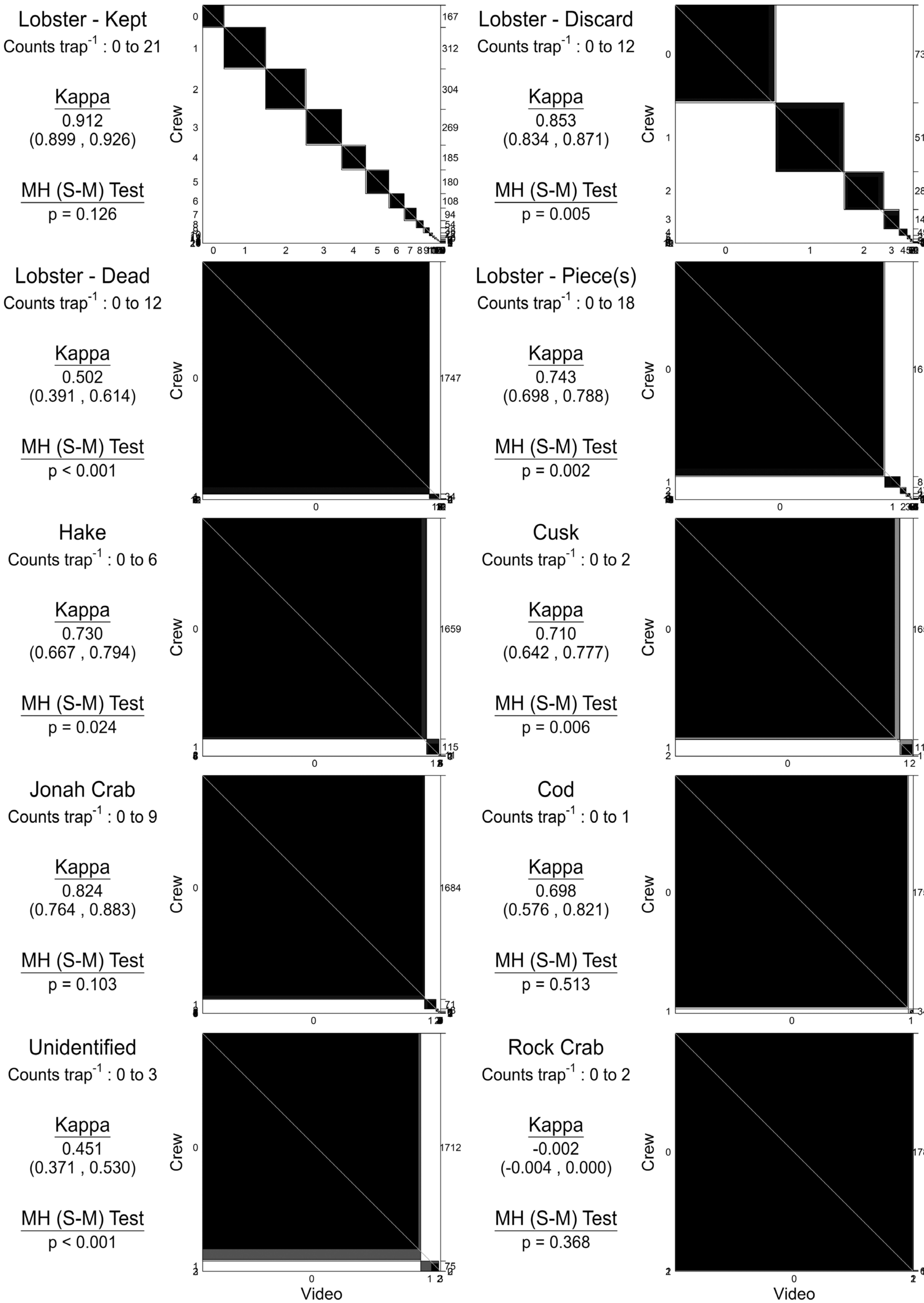

Fig. 2. Comparison of crew counts (Crew) to counts derived from electronically captured, independently assessed records (Video), conducted on 40 strings (10 randomly selected per quarter). Bangdiwala's agreement chart serves as a visual representation of the contingency table for each bycatch species. Black-filled rectangles represent frequencies of perfect agreement, while lighter grey (descending to white) rectangles show disagreement on an ordinal scale; the path of the rectangles (above or below the diagonal light-grey line) shows the direction of bias. For example, rectangles extending below the diagonal line indicate higher crew counts. The right y-axis provides the frequencies of crew-derived counts. Agreement was measured with Cohen's kappa, while symmetry was assessed with the marginal homogeneity (MH, Stuart-Maxwell) test

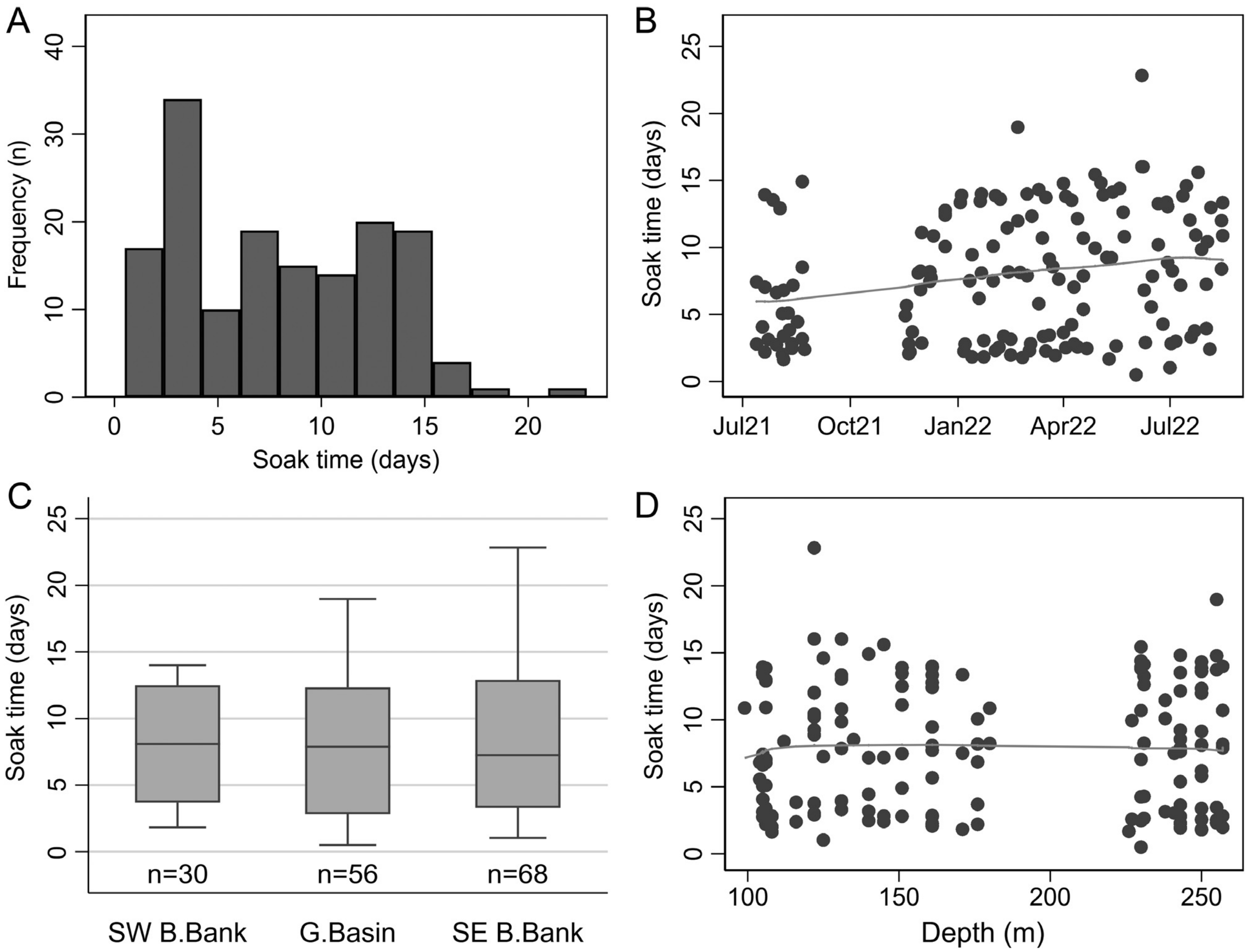

Fig. 3. Distributions of string-level soak times (A) over the entire study and (B) over time during the study. Strings were deployed in (C) 3 fishing areas (SW B. Bank: Southwest Browns Bank; G. Basin: Georges Basin; SE B. Bank: Southeast Browns Bank) and (D) at various depths. In (C), boxes represent the interquartile range (IQR), while the whiskers extend to the most extreme data points within 1.5 times the IQR. Horizontal grey lines in (B) and (D) represent locally weighted scatterplot smoothing estimates of soak times

lobsters (Thakur et al. 2017), and hence no controlled trials took place (Fig. 3).

The effect of soak time on trap-level non-lobster bycatch risk varied for each species (Table 2, Fig. 4). After accounting for potential confounders, soak times resulted in statistically significant differences in risk for cusk and unidentified species. Soaking traps for 2 vs 14 d increased the estimated risk of catching cusk from 0.8 to 1.8% (LRT; $p = 0.030$) and catching unidentified species from 2.5 to 4.9% ($p = 0.001$). The soak time trends, although non-significant, for white hake, Jonah crab, and Atlantic cod were negative over the 14 d (LRT; $p = 0.063$, $p = 0.399$, and $p = 0.373$, respectively), meaning that risk declined with increasing soak time. None of the predictors, including soak times, nor any of the confounders or contextual effect (i.e. average number of live lobsters per trap on a string), were significant for rock crab, likely due to the very low risk of catching rock crab (~1%).

The most common, and highly significant, predictor for risk of bycatch was the fishing area, with varying risk according to the species. For example, white hake had higher risk in Georges Basin (11.4%) and SE Browns Bank (14.0%) than in SW Browns Bank (1.5%; Fig. 5B, WH-2); cusk had the highest risk in SW Browns Bank (2.8%), followed by Georges Basin (1.7%), and SE Brown Bank (0.3%; Fig. 5F, Ck-2); Jonah crab had the lowest risk in Georges Basin (2.3%), compared to SW and SE Browns Bank (5.9 and 6.9%, respectively; Fig. 5H, JC-2); and unidentified species had the lowest risk in SE Browns Bank (1.8%)

Table 2. Estimates of the effect of soak time on the probabilities of bycatch in lobster traps (n = 7674) from mixed logistic regression models with string as a random effect (n = 154). Significant confounders are outlined for each model, encompassing date, fishing area (SW Browns Bank, Georges Basin, and SE Browns Bank), depth (m) (back-transformed, $m^{-2} \times 10000$), presence of lobster in the trap (0 or 1), and a string-level contextual effect summarizing the average number of live lobsters per trap. 'Reference' indicates that SW Browns Bank serves as the reference fishing area for comparisons with Georges Basin and SE Browns Bank. Results are visually depicted in Fig. 4 (soak time) and Fig. 5 (confounders)

	White hake	Cusk	Jonah crab	Atlantic Cod	Unidentified	Rock crab
Soak time (d)	Fig. 4A	Fig. 4B	Fig. 4C	Fig. 4D	Fig. 4E	Fig. 4F
Coef.	−0.0377	0.0716	−0.0221	−0.0344	0.0587	0.1183
SE	0.0201	0.0327	0.0259	0.0361	0.0174	0.0918
p[a]	0.063	0.030	0.399	0.341	0.001	0.178
Date	Fig. 5A		Fig. 5G	Fig. 5J		
Coef.	−0.0022		−0.0083	0.0043		
SE	0.0009		0.0010	0.0018		
p	0.010		<0.001	0.017		
Fishing area	Fig. 5B p < 0.001	Fig. 5F p < 0.001	Fig. 5H p < 0.001		Fig. 5M p < 0.001	
SW Browns Bank	Reference	Reference	Reference		Reference	
Georges Basin						
Coef.	1.6202	−0.5478	−1.0086		0.4031	
SE	0.3157	0.3590	0.3403		0.2621	
p	<0.001	0.127	0.003		0.124	
SE Browns Bank						
Coef.	1.8182	−2.4390	0.1846		−1.3661	
SE	0.3596	0.4278	0.2941		0.3253	
p	<0.001	<0.001	0.530		<0.001	
Depth (m)	Fig. 5C				Fig. 5N	
Coef.	2.7445				2.8279	
SE	0.6238				0.6783	
p	<0.001				<0.001	
Lobster (0 or 1)	Fig. 5D		Fig. 5I	Fig. 5K		
Coef.	−0.3123		−0.3395	−0.4734		
SE	0.1213		0.1391	0.2319		
p	0.010		0.015	0.041		
Contextual Eff. (avg. lobster trap^{-1})	Fig. 5E			Fig. 5L		
Coef.	−0.2697			−0.3086		
SE	0.0479			0.0913		
p	<0.001			0.001		
Constant						
Coef.	46.6202	−4.1633	185.4271	−100.3712	−4.6364	−8.9942
SE	19.4294	0.4135	23.6373	40.7693	0.3590	1.2080
Random effect						
Variance	0.7716	1.5495	1.2765	1.9584	0.4274	9.8698
SE	0.1462	0.4094	0.2671	0.5464	0.1152	4.0025

[a]Likelihood ratio tests were used for soak time

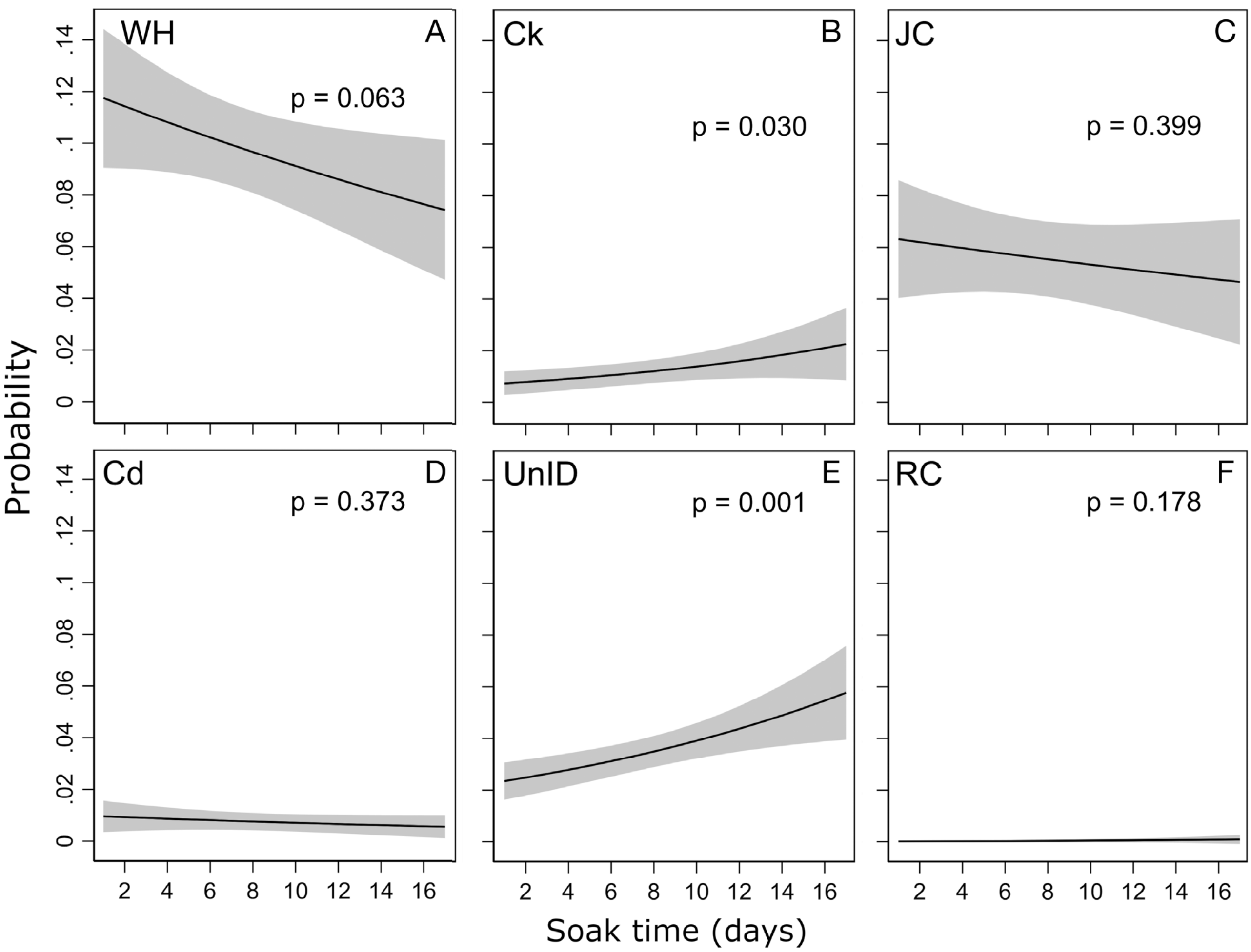

Fig. 4. Estimated effects of soak times on the probabilities of having bycatch in a trap (n = 7674) for (A) white hake (WH), (B) cusk (Ck), (C) Jonah crab (JC), (D) Atlantic cod (Cd), (E) unidentified (UnID), and (F) rock crab (RC). Models used mixed logistic regression with string as a random effect, and p-values were derived from likelihood ratio tests. Significant confounders were included in each model (see Table 2, Fig. 5);grey shaded areas: 95% CI

compared to SW Browns (6.6%) and Georges Basin (9.4%; Fig. 5M, UnID-2). In addition to the fishing area, depth was also a highly significant (Wald test; $p < 0.001$) negative predictor for both white hake and unidentified species (Fig. 5C,N, WH-3 and UnID-3, respectively), with a considerable decrease in risk from 26.0 to 3.8% and from 17.4 to 2.0%, respectively, when depth increased from 95 to 250 m. Date was a significant predictor for white hake, Jonah crab, and Atlantic cod; it was negatively associated with bycatch risk for white hake and Jonah crab (Fig. 5A,G, WH-1 and JC-1, respectively) and positively associated with bycatch risk for Atlantic cod (Fig. 5J, Cd-1).

The presence of any live lobster in the trap (i.e. species interactions) was consistently negatively associated with bycatch risk for white hake, Jonah crab, and Atlantic cod (Wald test; $p = 0.010$, $p = 0.015$, and $p = 0.041$, respectively), and the contextual effect (string-level average number of lobsters per trap) was also negatively associated with bycatch risk for white hake and Atlantic cod (Wald test; $p < 0.001$ and $p = 0.001$, respectively; Fig. 5E,L, WH-5 and Cd-5, respectively).

For the targeted species, i.e. lobsters, the effect of soaking traps for 14 d increased the estimated probability of marketable (kept) lobsters from 78.4% on Day 2 to 88.2% on Day 14 (LRT, $p = 0.002$) (Table 3, Fig. 6A, L_ka). Over the same time interval (Days 2–14), increased soak times were also significantly associated with increased probabilities of capturing discarded live lobsters (from 43.5 to 59.2%; Wald test, $p = 0.002$), dead lobsters (from 0.4 to 2.6%; Wald test, $p < 0.001$), and pieces of lobster in hauled traps (from 2.4 to 15.7%; Wald test, $p < 0.001$) (Fig. 6A, L_da, L_dd, and L_p, respectively).

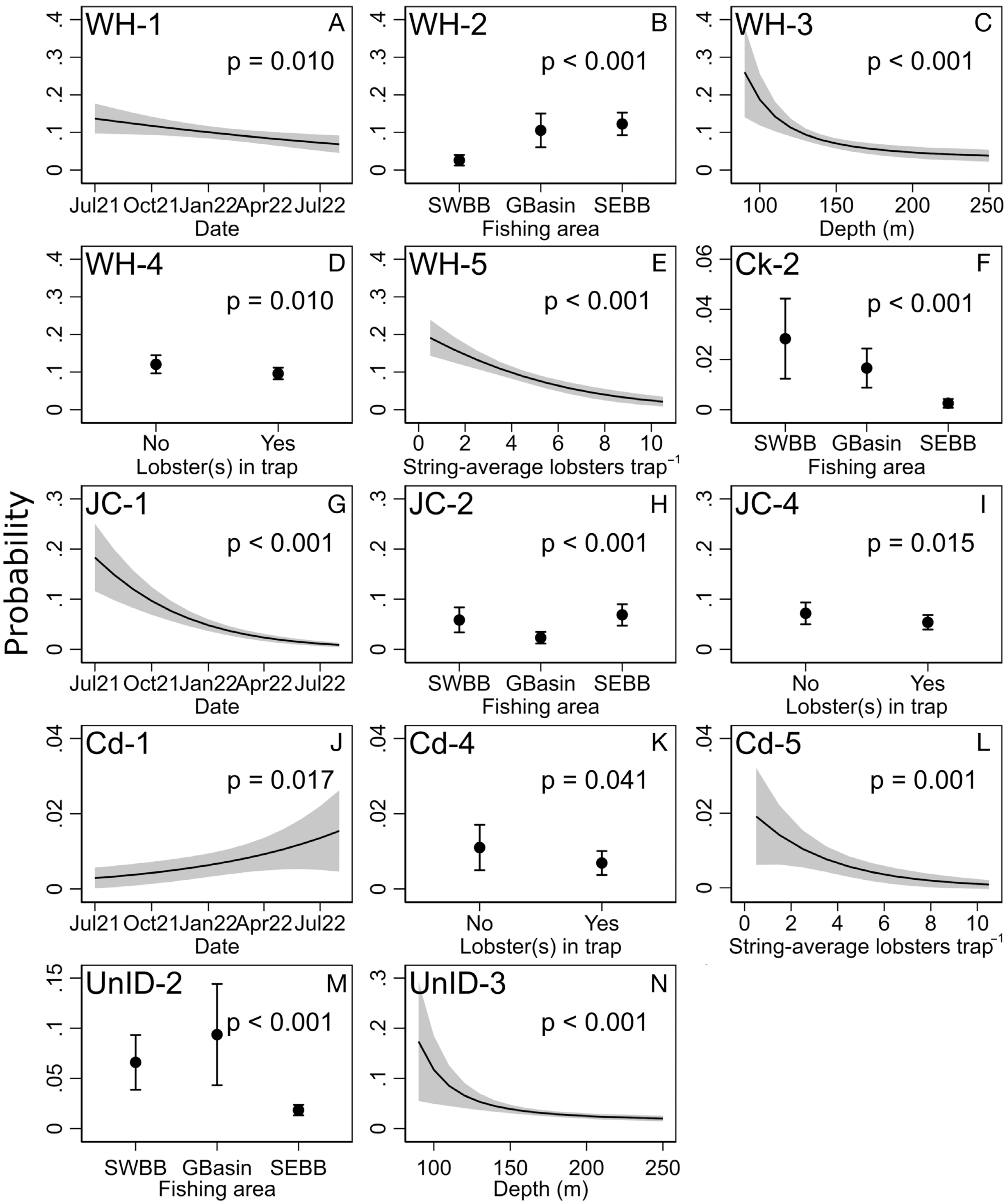

Fig. 5. Estimated effects of significant confounders on the probabilities of having (A–E) white hake, (F) cusk (G–I) Jonah crab, (J–L) Atlantic cod, and (M–N) unidentified bycatch in a trap (n = 7674). Models used mixed logistic regression with string as a random effect (see Table 2). Label letters and numbers indicate species (WH: white hake; CK: cusk; JC: Jonah crab; Cd: Atlantic cod; UnID: unidentified) and confounders (1: date; 2: fishing area [SWBB: Southwest Browns Bank; GBasin: Georges Basin; SEBB: Southeast Browns Bank]; 3: depth [back-transformed]; 4: lobster presence; 5: a string-level contextual effect summarizing the average number of live lobsters per trap). Grey shaded areas and vertical bars: 95% CI

Table 3. Estimates of the effect of soak time on the probabilities of lobsters (kept, discarded, dead, pieces) in traps (n = 7674) from mixed logistic regression models with string as a random effect (n = 154). Significant confounders include date and fishing area (SW Browns Bank, Georges Basin, and SE Browns Bank). 'Reference' indicates that SW Browns Bank serves as the reference fishing area for comparisons with Georges Basin and SE Browns Bank. Results are visually depicted in Fig. 6

	Lobster kept (alive)	Lobster discarded (alive)	Lobster dead	Lobster pieces
Soak time (days)	Fig. 6A (L_ka)	Fig. 6A (L_da)	Fig. 6A (L_dd)	Fig. 6A (L_p)
Coef.	0.4093[a]	0.0542	0.1593	0.1721
SE	0.1329[a]	0.0168	0.0333	0.0206
p[b]	0.002	0.002	< 0.001	< 0.001
Date		Fig. 6B (L_da-1)		Fig. 6B (L_p-1)
Coef.		0.0036		0.0032
SE		0.0007		0.0009
p		<0.001		<0.001
Fishing area	Fig. 6B (L_ka-2) p = 0.002	Fig. 6B (L_da-2) p = 0.042		
SW Browns Bank	Reference	Reference		
Georges Basin				
Coef.	0.7224	−0.2544		
SE	0.2761	0.2264		
p	0.009	0.261		
SE Browns Bank				
Coef.	0.9399	0.1803		
SE	0.2683	0.2161		
p	<0.001	0.404		
Constant				
Coef.	0.3342	−81.8631	−5.8371	−76.3380
SE	0.3388	16.0890	0.3843	19.3345
Random effect				
Variance	1.2771	0.8051	1.6218	0.8776
SE	0.1852	0.1091	0.3862	0.1581

[a]Days were ln-transformed for kept lobsters; [b]Likelihood ratio test was used for soak time

The only remaining significant predictor for the probability of hauled traps to have marketable lobsters (kept) was the fishing area (Wald test, $p < 0.002$), where Georges Basin and SE Browns Bank had more traps with marketable lobsters than from the SW Browns Bank fishing area (Table 3, Fig. 6B, L_ka-2). For discarded (live) lobsters, fishing area was a significant predictor (Wald test, $p = 0.042$); Georges Basin had fewer traps with discarded lobsters than SE Browns Bank. The date hauled was significant for both discarded lobsters and pieces of lobsters (Wald test, $p < 0.001$), with steadily increasing estimated probabilities over the 1 yr period (Table 3, Fig. 6B, L_da-1). However, when restricting dates between 15 August 2021 and 15 August 2022 (to represent one complete year without seasonal overlap) and adding a second fractional polynomial term for date, the discarded lobster relationship showed a seasonal u-shaped pattern, as was expected from multi-year offshore industry observations—the resulting non-linear relationship (Wald test, $p < 0.001$) is presented in Fig. 6B (L_da-1) as a dashed line.

3.3. Power analyses

Power estimates used to indicate the probability of detecting a true effect were conducted on 106 strings

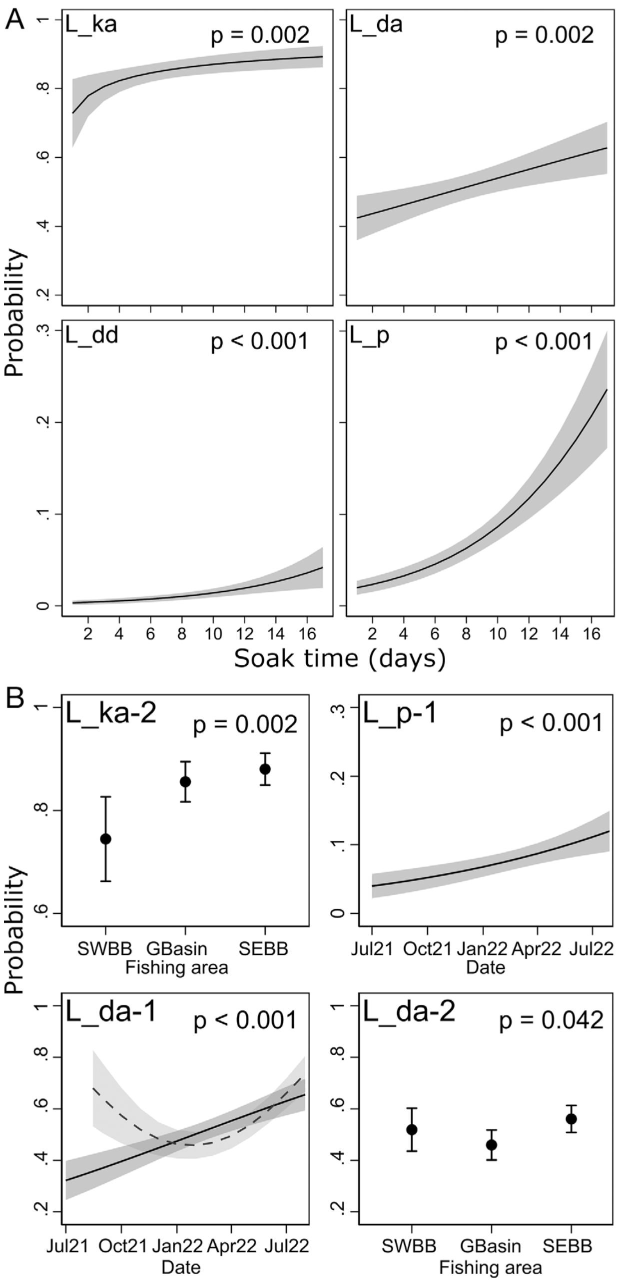

Fig. 6. Estimated effects of (A) soak times and (B) significant confounders on the probability of having at least one marketable (kept alive; L_ka), discarded alive (L_da), dead (L_dd), or piece(s) of (L_p) lobster in a trap (n = 7674). Models used mixed logistic regression with string as a random effect (see Table 3). Label numbers correspond to the confounders date (1) and fishing area (2) (see Fig. 5). Grey shaded areas and vertical bars: 95% CI. Dashed line: estimates for a subset of discarded alive lobsters (15 August 2021 to 15 August 2022) modeled with 2 fractional polynomial terms (−2, −2)

midway through the study and demonstrated sufficient power (at the 80% threshold) for half the bycatch species: 94.1% for unidentified species, 90.4% for white hake, 81.5% for cusk, 43.1% for Jonah crab, 5.0% for Atlantic cod, and 0.2% for rock crab (Table 4). Unconditional trends for soak times revealed that for some bycatch, soak times acted as risk factors (positive association), while for others, they were protective (negative association). Given the varying soak time trends and sufficient power for half of the bycatch, data collection concluded at the 1 yr mark, encompassing all seasons except September and October 2021.

At the end of data collection, with all 154 strings deployed, estimated powers for observed soak time coefficients were 91.7% for white hake, 87.8% for unidentified species, 61.0% for cusk, 50.5% for Jonah crab, 18.8% for Atlantic cod, and 0.0% for rock crab. The reduction in power for cusk, rock crab, and unidentified species between midway and final analyses was attributed to reduced soak time coefficients in the final model compared to midway analyses. In other words, the reduced impact of soak times observed at the study's end undermined the power to detect a difference. Simulations with fixed coefficients at 0.105, 0.080, and 0.050 demonstrated that except for rock crab, sample sizes were sufficient (at 80% power) to detect an approximate quadrupling of bycatch risk over the 14 d soak time (at coefficients fixed at 0.105) and tripling of the risk for white hake and unidentified bycatch species (at coefficients fixed at 0.080) (Table 4).

3.4. Predictions for fishing in LFA 41

Commercial operations in LFA 41 conducted 177 980 trap hauls between July 2021 and August 2022, across 1486 strings (Fig. 7). The average soak time was 7.5 d, with an average depth of 195 m, landing an average of 4.25 lobsters per trap (Table 5). Most trap hauls were in the SE region of Browns Bank (55.3%), followed by Georges Basin (30.3%), the SW region of Browns Bank (11.9%), and Georges Bank (2.5%). Based on these averages (assumed to be constant for the modeled estimates), the predicted number of traps hauled with bycatch is presented in Table 6 for those bycatch species with significant effects from soak time, corresponding to the estimated bycatch weights for LFA 41 in this period (cusk: 3641 kg; unidentified species: 2658 kg; Table 6). Relative weights (%), compared to the marketable lobsters, are presented for each bycatch species to serve as a comparison among the mandated soak time, the commercial average, and the study's aimed maximum of 14 d.

Table 4. Power estimates from both midway (n = 106 strings) and end-of-study (n = 154 strings) analyses are provided for unconditional associations of soak time on probabilities of bycatch in traps. Soak time coefficients (expressed in logits) were derived from mixed logistic regression models with string as a random effect. Simulated soak time coefficients of 0.050, 0.080, and 0.105 were used to represent approximate doubling, tripling, and quadrupling of the risk of bycatch over a 14 d period. UnID: unidentified

		Midway: soak time			Simulated: soak time			End: soak time	
					Power (95% CI)				
	Strings n	Coef. (p)	Power (95% CI)	Strings n	Coef. = 0.105	Coef. = 0.080	Coef. = 0.050	Coef. (p)	Power (95% CI)
White Hake	106	−0.1308 (<0.001)	90.4% (88.4, 92.2)	154	97.4% (96.2, 98.3)	85.1% (82.7, 87.3)	43.9% (40.8, 47.0)	−0.0942 (0.001)	91.7% (89.8, 93.3)
Cusk	106	0.1251 (0.005)	81.5% (79.0, 83.9)	154	82.2% (79.7, 84.5)	56.7% (53.6, 59.8)	25.3% (22.6, 28.1)	0.0830 (0.026)	61.0% (57.9, 64.0)
Jonah Crab	106	−0.0783 (0.090)	43.1% (40.0, 46.2)	154	90.2% (88.2, 92.0)	68.7% (65.7, 71.6)	35.2% (32.2, 38.3)	−0.0688 (0.052)	50.5% (47.4, 53.6)
Atlantic Cod	106	0.0035 (0.935)	5.0% (3.7, 6.5)	154	89.3% (87.2, 91.2)	66.5% (63.5, 69.4)	30.8% (28.0, 33.8)	−0.0429 (0.263)	18.80% (16.4, 21.4)
UnID	106	0.0769 (<0.001)	94.1% (92.5, 95.5)	154	100.0% (99.6, 100.0)	99.5% (98.8, 99.8)	77.5% (74.8, 80.1)	0.0560 (0.002)	87.8% (85.6, 89.8)
Rock Crab	106	0.0776 (0.539)	0.2% (0.0, 0.7)	154	0.0% (0.0, 0.4)	0.0% (0.0, 0.4)	0.0% (0.0, 0.4)	0.0594 (0.581)	0.0% (0.0, 0.4)

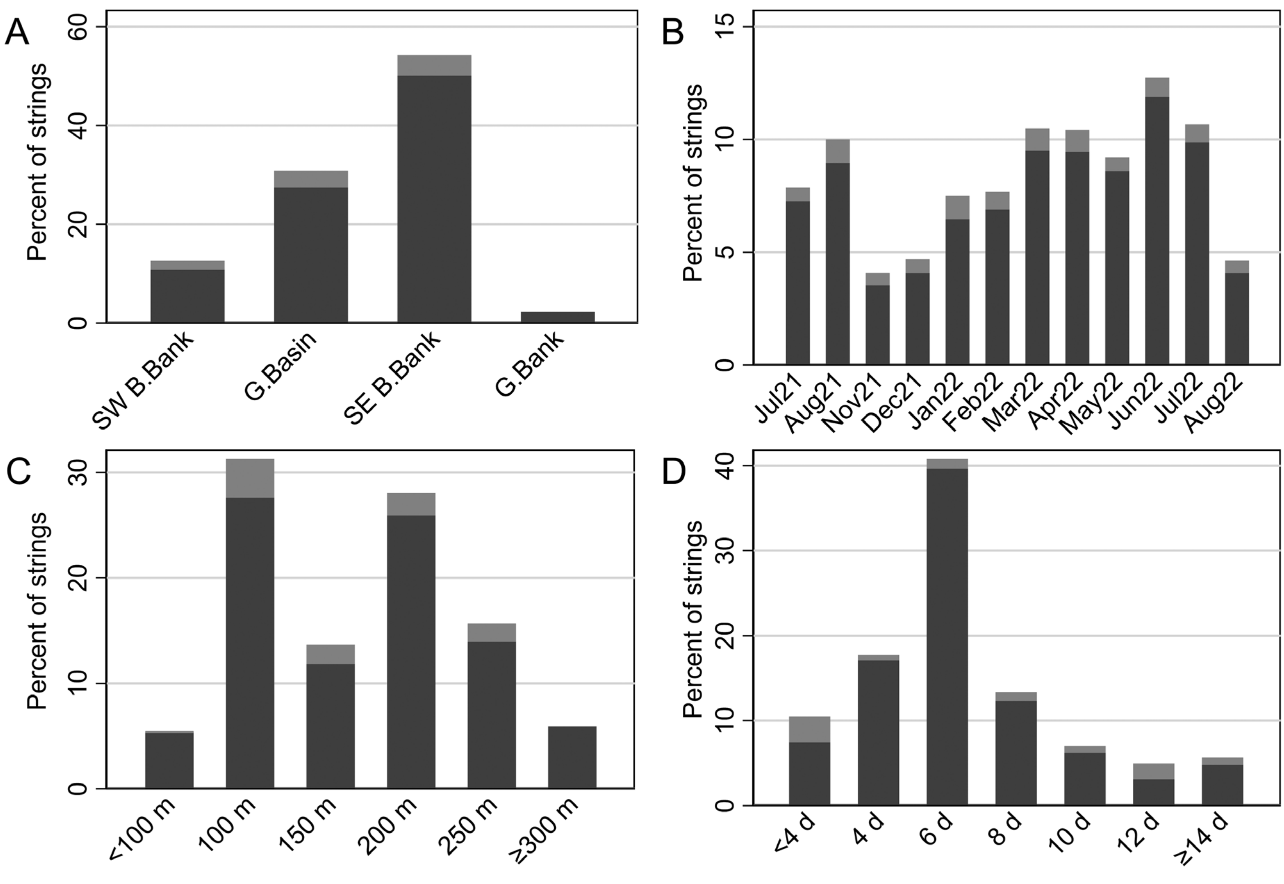

Fig. 7. Bar graphs show the percent of strings deployed in LFA 41 between July 2021 and August 2022 for the whole offshore industry (bottom; dark grey; n = 1486) compared to the bycatch study (top; light grey; n=154). The distribution is across (A) fishing areas, (B) dates, (C) depths, and (D) soak times

Table 5. Summary statistics for soak time and potential confounders from LFA 41 commercial operations between July 2021 and August 2022 (n = 1486 strings, for a total of 177980 traps), and proportions of landed traps across the 4 fishing areas

	Mean	SD
Soak time (d)	7.50	2.85
Date	01 Mar 2022	119 d
Depth (m)	195.14	76.88
Average lobsters trap^{-1}	4.25	2.19
Average traps string^{-1}	119.77	2.13
Fishing area	Proportion	
SW Browns Bank	0.119	
Georges Basin	0.303	
SE Browns Bank	0.553	
Georges Bank	0.025	

4. DISCUSSION

This study represents the most extensive investigation into trap-level bycatch data within the Canadian offshore lobster industry. Undertaken as a 1 yr controlled trial, the primary aim was to scrutinize the influence of soak times on bycatch risk, providing valuable insights for effective fisheries management strategies. The results revealed nuanced associations between soak times and bycatch risk across various non-target species and discarded target species, including lobsters (kept alive, discarded alive, dead, and pieces).

The prevalence of traps with bycatch remained relatively modest, ranging from 11.5% for white hake to 1.0% for rock crab. This underscores the importance of incorporating numerous traps and strings over the study's 1 yr duration. End-of-study power calculations revealed sufficient sample sizes, except for rock crab, that would enable the detection of a fourfold increase in bycatch risk over a 14 d period, and a threefold increase specifically for white hake and unidentified bycatch species. Soak time was a significant factor for the risk of bycatch of cusk and unidentified species. Nevertheless, the observed low percentages (0.8–1.8% for cusk and 2.5–4.9% for unidentified species) suggest a relatively minimal impact, even with increased soak times.

This study found no conclusive evidence that soak times at least quadrupled the risk of catching white hake, Jonah crab, or Atlantic cod over the 14 d period. However, prolonged soak times substantially elevated the prevalence of traps containing lobsters, rising from 78% (Day 2) to 88% (Day 14). This increase correlated with higher probabilities of discovering live lobsters (45–59%), dead lobsters (~0–3%), and pieces of lobster (2–16%).

Examining the potential repercussions of soak time reduction in LFA 41, estimates indicated that decreasing the soak time average from 7.5 to 3 d would reduce cusk and unidentified bycatch by approximately 1.0 t (965 kg; from 3627 to 2662 kg) and 0.6 t (604 kg; from 2663 to 2059 kg), respectively. However, a reduction in soak time would also decrease landed lobster by 32.8 t (32882 kg; reducing from 544352 to 511470 kg; Table 6), necessitating more trap hauls to meet the total allowable catch. It is noteworthy that while achieving the TAC would require additional fishing effort, the total number of traps with bycatch (for both cusk and unidentified species) would decrease, as the proportions of traps with bycatch relative to total traps decrease after 3 d of soak time (1.09% for cusk; 1.94% for unidentified species) compared to 7.5 d (1.39% for cusk; 2.35% for unidentified species). In terms of biomass, reducing soak time from 7.5 to 3 d would likely require increased fishing effort, which could mitigate some of the expected reductions in bycatch. However, the projected reductions include 171 kg of cusk and 472 kg of unidentified species for LFA 41. The tradeoff between modest reductions in cusk and unidentified species bycatch biomass needs careful consideration against increased fishing effort. Such considerations should align with fisheries management objectives, encompassing fishery footprint, right whale risk mitigation, and broader societal goals, including economic and environmental impacts such as carbon footprint. Weighing these factors comprehensively is essential for informed decision-making in the context of sustainable fisheries management.

Comparing the study's estimated bycatch rates (biomass) to reported rates in LFA 41 from DFO, the impact of soak time appears notably low, especially when considering DFO's expected annual variation in bycatch rates. Additionally, when contrasted against the trends of the last 2 decades, during which substantial reductions in bycatch rates occurred, changing soak time from 7.5 to 3 d exhibited a minimal impact on bycatch rates. To illustrate this point, DFO's estimated annual bycatch weights for cusk in LFA 41 was 23.3 t between 2008 and 2010, 11.9 t between 2011 and 2013, 5.8 t between 2014 and 2016 (DFO 2018), and more recently, 8.1 t between 2018 and 2022 (DFO 2023). While these data suggest that soak time has a limited impact on bycatch biomass, it is important to acknowledge that the bycatch weights in our study were crew-derived estimates based on

Table 6. Predicted impact of commercial lobster fishing soak time on bycatch in LFA 41 between July 2021 and August 2022, for bycatch species with statistically significant soak time effects. Probabilities of bycatch being present in traps were estimated from mixed logistic regression models (see Tables 2 & 3), with 3 possible soak times, set at the mandated limit (3 d), the commercial average (7.5 d), and the study maximum (14 d), for a total of 177 980 trap hauls. Estimated weights for LFA 41 were calculated by multiplying the estimated number of trap hauls (with at least one bycatch animal) in LFA 41 by the average weights from the study traps with at least one bycatch animal (see Table 1). 'Reference' indicates that relative weights (%) for bycatch species are expressed relative to the retained lobster weight

		Cusk	Unidentified	Lobsters kept	Lobsters discarded	Lobsters dead
Soak time	Weight (kg) trap^{-1a}	1.748	0.754	3.703	1.899	1.260
3 days	Probability	0.009	0.015	0.776	0.473	0.010
	95% CI	0.004, 0.013	0.009, 0.022	0.736, 0.817	0.424, 0.522	0.005, 0.015
	Traps (n) with bycatch	1523	2731	138123	84195	1805
	Weight (kg) for LFA 41	2662.2	2059.2	511469.5	159886.3	2274.3
	Relative weight (%)^{b}	0.52	0.40	Reference	31.26	0.44
7.5 days	Probability	0.012	0.020	0.826	0.525	0.020
	95% CI	0.007, 0.016	0.012, 0.027	0.800, 0.852	0.492, 0.559	0.014, 0.026
	Traps (n) with bycatch	2075	3532	147003	93440	3556
	Weight (kg) for LFA 41	3627.1	2663.1	544352.1	177442.6	4480.6
	Relative weight (%)^{b}	0.67	0.49	Reference	32.60	0.82
14 days	Probability	0.018	0.029	0.855	0.599	0.051
	95% CI	0.009, 0.027	0.017, 0.040	0.0823, 0.887	0.548, 0.650	0.031, 0.070
	Traps (n) with bycatch	3221	5102	152189	106591	8990
	Weight (kg) for LFA 41	5630.3	3846.9	563555.9	202416.3	11327.4
	Relative weight (%)^{b}	1.00	0.68	Reference	35.92	2.01

[a]Taken directly from Table 1; [b]Relative to kept lobster weight

sight and feel, and thus likely contain inherent errors. However, these estimates remain valuable for providing a general sense of the magnitude of bycatch at the regional level, offering crucial context for understanding trends.

Estimates for LFA 41 derived from the study were more conservative for cusk, Jonah crab, and discarded lobsters (by factor of approximately 3), and more liberal for white hake and Atlantic cod (by a factor of approximately 1.5) compared to DFO's latest estimates. Even accounting for a factor of 3 in the study estimates, the impact of soak time on bycatch in LFA 41 remains relatively low.

Various measured factors, included as potential confounders, emerged as robust predictors of bycatch risk, with some exerting larger impacts than soak time. Fishing area consistently stood out as a significant predictor, influencing white hake, cusk, Jonah crab, and unidentified species. Although no discernible pattern emerged across species, the variations in different areas possibly reflect diverse macro-environmental conditions conducive to each species. As an example, Runnebaum (2017) described the non-homogenous distribution of cusk bycatch in Maine lobster fishing operations. Depth strongly correlated with the risk of catching white hake and unidentified species, exerting the largest impact on their risk estimates. Date emerged as a significant predictor for white hake, Jonah crab, and Atlantic cod, with Jonah crab exhibiting the most substantial reduction in risk during the study's first 6 mo. The spatial predictors (fishing area and depth) and the temporal predictor (date) likely serve as surrogate measures for numerous unrecorded environmental and ecological conditions influencing local species abundances and population trends over time. The observed significance and impact of these spatiotemporal predictors underscore the importance of including such measures in bycatch studies.

Potential interactions between bycatch species and lobsters were explored analytically by incorporating a predictor for the presence of live lobster(s) (either kept and/or discarded) and introducing a contextual effect to capture the average number of lobsters per trap for the entire string. The presence of live lobsters (kept and/or discarded) in a trap was associated with reduced bycatch risk for white hake, Jonah crab, and Atlantic cod. Furthermore, higher average numbers of lobsters per trap significantly lowered the risk of bycatch for white hake and Atlantic cod. However, the study's design inhibits a clear distinction between protective and risk factors linked to the presence of lobsters in traps. It remains uncertain whether bycatch species were dissuaded from entering traps already occupied by lobsters or if they were consumed by lobsters once inside the trap. The study was likewise unable to determine the impact of bait over longer soak times, presuming that it would have reduced attractiveness with time, but unable to be verified by animal behavior in the trap. Similar uncertainty surrounds the contextual effect, making it impossible to discern the underlying biological mechanism, such as serving as a surrogate measure for increasing lobster densities in the immediate areas with fewer natural prey.

Spatiotemporal trends for lobsters demonstrated higher proportions of traps with market-size lobsters in Georges Basin, with lower probabilities of discarded lobsters in SE Browns Bank. These differences likely result from complex ecological factors within fishing areas. The study's limitations, confined to vessel-based data collection, hindered a comprehensive analysis of additional factors affecting catch rates, such as environmental conditions, molt stages, and reproductive states (Cook et al. 2020).

The independent assessment of the trap counts, derived from electronic monitoring in comparison to crew counts on board the vessel, offered a representative sample covering more than a quarter of the strings throughout the study. This assessment was crucial for ensuring transparency, validating results, and mitigating perceived bias due to the absence of blinding in crew observations. Overall, the agreement between video and crew counts was robust. As expected, distinctions were almost perfect for easily recognizable species like lobsters and Jonah crab, while challenges were encountered with rock crab. The limited presence of rock crabs and potential difficulty in correct classification from video footage contributed to the lower agreement in this category. Hake presented challenges in classification from video footage, particularly at the species level, resulting in their grouping. Interestingly, crew counts were higher than video counts for hake, further supporting the potential for misclassification of hake in the electronic records. Fair agreements were observed for unidentified species and dead lobsters, where video counts tended to surpass crew counts. The overrepresentation of unidentified species in video footage could stem from unclear identifications, possibly leading to misclassification. The classification of lobsters as dead on video, when crew members could distinguish their liveliness, contributed to discrepancies. Counting cusk, with substantial agreement, posed difficulties on video due to the rapid handling speed by crew members, impacting accurate counts. Similarly, the quick bundling of lobster pieces by crew members made it challenging to track on video.

These disparities may be attributed to differences in identification skills, attention to detail, and recording precision between the busy crew working at sea and experienced marine image annotators (Kindt-Larsen et al. 2012). Other studies have shown that scientific fishery observers given additional tasks deliver lower counts than those without additional tasks (CUD 1994). However, the crew's real-time feedback, such as distinguishing between alive and dead, and the ability to rapidly identify and count lobster pieces during bundling, are advantages that electronic monitoring may not fully capture. The logistics of video capture occasionally led to trap ID discrepancies, reducing agreement in matched traps. However, this discrepancy did not affect symmetry or introduce bias, underscoring the reliability of electronic monitoring for future bycatch estimates.

The conventional analysis of string-level bycatch often involves aggregate string weights, commonly referred to as catch levels (kg) and rates, utilizing the ratio method by dividing the weights of bycatch by landed lobsters (Pezzack et al. 2014). However, the richness of trap-level data, encompassing both weights and counts, coupled with the hierarchical structure of traps within strings, posed challenges for modeling weights. This complexity arises from the prevalence of zero counts (0 kg) in most traps, rendering zero-inflated negative binomial models suitable for count data with numerous zero counts. Yet incorporating random effects into such models, necessary to account for the clustering of traps within strings, becomes increasingly challenging. Despite sacrificing some information by using risk (probability of bycatch presence in a trap), employing mixed logistic regression models offered a robust analytical approach without compromising underlying statistical assumptions.

While typical limitations of studies often revolve around sample size and timeframe, our power analyses demonstrated sufficient power for 2 of the 5 bycatch species at tripling levels and 4 at quadrupling levels. Remarkably, even an additional 3 yr of data would not have enhanced our ability to detect a change in rock crab bycatch, given the exceedingly low risk with this species.

The collection of additional environmental information would have likely improved our predictive analyses. However, the study was confined to information available from commercial fishing operations, and it was not designed as an ecological study on the bycatch or lobster population in the fishing area.

An obvious limitation of this study lies in the absence of additional trap-level information during the soak time period at sea. The absence of a camera at the ocean floor precluded insights into whether bycatch repelled from traps or consumed when lobsters were present, leading to an underestimation of the impact of soak time in our study. Additionally, without a camera at the trap, it was impossible to observe catchability information (i.e. percent of animals caught compared to animals that have entered the traps), where one study reported keeping only 6% of lobsters that entered traps (Jury et al. 2001). Without such information, we could not describe trap catchability over space and time by species. The intricacies and challenges of deploying trap-level cameras at sea rendered this option unfeasible for this specific study. Future studies on bycatch stand to gain more information from incorporating such video-recording methods to capture trap-level dynamics at sea.

5. CONCLUSIONS

This study represents the most extensive examination of trap-level bycatch data within the Canadian lobster industry. Soak times were significantly associated with increased risk of capturing cusk and unidentified species. However, these associations, while statistically significant, translate into relatively minor implications for all harvesting in LFA 41 when contrasted with the substantial influence of factors like fishing area, depth, and temporal trends. In the broader context of fisheries management, it becomes essential to integrate these increased risks into the overall objectives of fishery sustainability. This involves not only understanding the direct impact on bycatch but also considering the secondary effects on catch rates and the resultant profile of total bycatch in the fishery. Moreover, historical evidence from decades of independent at-sea observer data emphasizes that other measures, like fleet rationalization and the concentration of footprint through trap reduction, have historically had a larger impact on bycatch rates than the observed changes from soak time alterations in this study. Acknowledging and leveraging such historical insights will be helpful for planning strategies for mitigating bycatch in lobster trap fisheries taking place in similar environmental and operational conditions.

Acknowledgements. Funding for this work was provided by Clearwater Seafoods. We thank the captain and crew of the 'Randell Dominaux' for their interest and dedication to data collection, Grant MacLeod with Clearwater for technical support on video monitoring, Evan Mosher with Clearwater for data acquisition on video monitoring, Travis Lowery from the University of Massachusetts Dartmouth (now with Vineyard Wind) for video and crew data comparisons, and Adam Cook with DFO for comments and suggestions on study design and data analyses. The views expressed herein are those of the authors and do not necessarily reflect the views of DFO. We also thank the 3 anonymous reviewers for their thoughtful and constructive feedback which improved the manuscript.

LITERATURE CITED

Anderson BN, Weissman AM, Sweezey B, Mandelman J, Rudders DB, Sulikowski JA (2020) Bycatch in a commercial lobster fishery: effects on two benthic predators, sea raven and longhorn sculpin. Mar Coast Fish 12:113–123

Bangdiwala SI (2017) Graphical aids for visualizing and interpreting patterns in departures from agreement in ordinal categorical observer agreement data. J Biopharm Stat 27:773–783

Bates D, Mächler M, Bolker B, Walker S (2015) Fitting linear mixed-effects models using lme4. J Stat Softw 67(1):1–48

Boenish R, Chen Y (2018) Quasi-stationary Atlantic cod bycatch estimation in the Maine American lobster *Homarus americanus* trap fishery. N Am J Fish Manage 38:3–17

Boudreau SA, Hanley PH (2023) Baseline composition, quantity, and condition of bycatch in the southern Gulf of St. Lawrence spring and summer American lobster fisheries. Facets 8:1–17

Choudhary PK, Nagaraja HN (2017) Measuring agreement: models, methods and applications. John Wiley & Sons, Hoboken, NJ

Cook AM, Cassista Da-Ros M, Denton C (2017) Framework assessment of the offshore American lobster (*Homarus americanus*) in Lobster Fishing Area (LFA) 41. DFO Can Sci Advis Sec Res Doc 2017/065

Cook AM, Hubley PB, Denton C (2020) 2017 Assessment of the offshore American lobster (*Homarus americanus*) in Lobster Fishing Area (LFA) 41. DFO Can Sci Advis Sec Res Doc 2018/034

CUD (Conservation and Utilization Division) (1994) Estimating harbor porpoise bycatch in the Gulf of Maine sink gillnet fishery. Northeast Fisheries Science Center (NEFSC) Ref Doc 94-24. NOAA/NMFS/NEFSC, Woods Hole, MA

DFO (Fisheries and Oceans Canada) (2000) LFA 41 offshore lobsters. DFO Science Stock Status Report C3-14(2000)

DFO (2008) Recovery potential assessment for cusk (*Brosme brosme*). DFO Can Sci Advis Sec Sci Advis Rep 2008/024

DFO (2018) Assessment of lobster (*Homarus americanus*) in Lobster Fishing Area 41 (4X + 5Z) for 2016. DFO Can Sci Advis Sec Sci Advis Rep 2018/004

DFO (2020) Stock status update of American lobster (*Homarus americanus*) in Lobster Fishing Area 41 (4X + 5Zc). DFO Can Sci Advis Sec Sci Res 2020/024

DFO (2023) Stock status update of lobster (*Homarus americanus*) in Lobster Fishing Area 41 (4X + 5Ze) for 2022. DFO Can Sci Advis Sec Sci Res 2023/012

Dohoo I, Martin W, Stryhn H (2009) Veterinary epidemiologic research, 2nd edn. Atlantic Veterinary College, Charlottetown

ESRI (Environmental Systems Research Institute) (2022) Ocean Basemap. ESRI, Redlands, CA. hub.arcgis.com/maps/6ac8d7bf0ae3469db2ece8e360c6cc30/explore?location=35.875372%2C-111.078800%2C6.06 (accessed 4 Nov 2022)

GIMP Development Team (2022) GNU image manipulation program v2.10.32. https://www.gimp.org

Green P, MacLeod CJ (2016) simr: an R package for power analysis of generalised linear mixed models by simulation. Methods Ecol Evol 7:493–498

Hijmans R (2023) raster: geographic data analysis and modeling. R package version 3.6-26. https://CRAN.R-project.org/package=raster

Jury SH, Howell H, O'Grady DF, Watson WH III (2001) Lobster trap video: *in situ* video surveillance of the behavior of *Homarus americanus* in and around traps. Mar Freshw Res 52:1125–1132

Kindt-Larsen L, Dalskov J, Stage B, Larsen F (2012) Observing incidental harbour porpoise *Phocoena phocoena* bycatch by remote electronic monitoring. Endang Species Res 19:75–83

Landis JR, Koch GG (1977) An application of hierarchical kappa-type statistics in the assessment of majority agreement among multiple observers. Biometrics 33:363–374

Maxwell AE (1970) Comparing the classification of subjects by two independent judges. Br J Psychiatry 116:651–655

Meyer D, Zeileis A, Hornik K, Friendly M (2023) vcd: visualizing categorical data. R package version 1.4-12. https://CRAN.R-project.org/package=vcd

Pezzack DS, Frail CM, Reeves A, Tremblay MJ (2009) Offshore lobster in Lobster Fishing Area 41 (4X and 5Zc). DFO Can Sci Advis Sec Res Doc 2009/023

Pezzack DS, Denton CM, Tremblay MJ (2014) Overview of by-catch and discards in the Maritimes region Lobster Fishing Areas (LFAs) 27–33 based on Species at Risk Act (SARA) at-sea sampling 2009–2010. DFO Can Sci Advis Sec Res Doc 2014/040

Pezzack DS, Denton C, Cassista-Da Ros M, Tremblay MJ (2015) Assessment of the Canadian LFA 41 offshore lobster (*Homarus americanus*) fishery (NAFO Divisions 4X 5Zc). DFO Can Sci Advis Sec Res Doc 2015/066

QGIS Development Team (2022) QGIS geographic information system. Open Source Geospatial Foundation Project. http://qgis.osgeo.org

R Core Team (2022) R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna

Runnebaum JM (2017) Improving management and conservation of cusk (*Brosme brosme*): habitat distribution, bycatch interactions, and conservation practices. PhD dissertation, University of Maine, Orono, ME

StataCorp (2022) Stata Statistical Software, release 17. StataCorp, College Station, TX. https://www.stata.com/

Stuart A (1955) A test for homogeneity of the marginal distributions in a two-way classification. Biometrika 42:412–416

Sweezey BB, Capizzano CW, Langan JA, Benoît HP and others (2020) Estimating the discard mortality of Atlantic cod in the southern Gulf of Maine commercial lobster fishery. N Am J Fish Manage 40:1252–1262

Thakur KK, Revie C, Stryhn H, Tibbetts SS, Lavallée J, Vanderstichel R (2017) Risk factors associated with soft-shelled lobsters (*Homarus americanus*) in southwestern Nova Scotia, Canada. Facets 2:15–33

Editorial responsibility: Romuald Lipcius, Gloucester Point, Virginia, USA
Reviewed by: J. Runnebaum and 2 anonymous referees
Submitted: March 19, 2024; Accepted: January 16, 2025
Proofs received from author(s): March 9, 2025