The distribution and direct impacts of marine debris on the commercial shrimping industry

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Abstract:

Commercial shrimpers frequently encounter marine debris in their nets, resulting in the loss of time and catch, and added repair costs. Before this study, no information existed on the spatial and temporal distribution of marine debris that shrimpers encounter and the subsequent economic impact on commercial shrimping. To characterize the quantity and impacts of marine debris, twenty commercial shrimpers participated in a comprehensive data collection program (July 2020 through December 2020) within the north-central Gulf of Mexico, USA. Results showed that derelict crab traps were an overwhelming issue for shrimpers, and the type of fishing gear used (skimmer vs. otter trawls) influenced both the type of marine debris encountered and the subsequent economic impacts. Surveyed shrimpers encountered marine debris on 19% of tows and lost an average of 18.21 minutes, 7.88 kg of catch, and $6.37 (USD) in gear damage per tow with encounters, resulting in average annual losses of $6,601 (USD) per shrimper.

Keywords: derelict fishing gear, commercial fishing, lost time, lost catch

1. Introduction

Commercial seafood industries have shaped cities and economies along coastlines worldwide. Along the US Gulf Coast, commercial seafood industries have not only established economies but also have immense cultural significance (Davis 2017; Stephens 2021). The shrimping industry is the most economically valuable of fishing industries along the US Gulf Coast and South Atlantic (NOAA 2020). In Mississippi alone, the entire seafood industry contributed a total of $465.4 million (USD) to the state's economy in 2015 this includes harvesting; processing and dealing; importing; wholesale and distributing; and retailing for all commercially fished species. The shrimping industry accounted for over 46% of that total with a total of $215.4 million (USD) (Posadas 2017). Shrimp harvesting alone created a total of $19.7 million (USD) in sales impacts and 367 job impacts in 2015 (Posadas, 2017). However, this industry is fragile and is exposed to a variety of natural and anthropogenic stressors including lack of stewardship practices, climate change, severe weather, varying and evolving regulations, and ocean pollution (Blasiak et al. 2021; Eriksen et al. 2014; Rozier 2021), which has led to steady declines in the number of Mississippi shrimpers and associated landings over the last 16 years with a current fleet of 120 commercial shrimpers (Posadas 2013; MDMR 2021).

One stressor that shrimpers must adapt to is marine debris. Marine debris is defined as any persistent solid material that is manufactured or processed and directly or indirectly, intentionally, or unintentionally, disposed of or abandoned in any ocean, on the seafloor, and/or on beaches worldwide (33 U.S.C. 1951-1958 (2006)). Marine debris and its impacts can be found on virtually any ocean, seafloor, and beach worldwide. Estimates show that about 6.4 million anthropogenic tons of litter end up in the oceans annually, most of which are primarily plastic and other hard, durable materials (Beiras 2018; Kaza et al. 2018). With the continued increasing production of plastics, the generation of marine debris will likely increase as well (Law et al. 2020).

Abandoned, lost, or otherwise discarded fishing gear (ALDFG) or derelict fishing gear has been an issue throughout the world's seas since fishing began (Macfadyen et al. 2009). Derelict fishing gear (DFG) is one common type of marine debris shrimpers encounter (Posadas et al. 2021; Guillory et al. 2001); DFG is any recreational or commercial fishing equipment that has been lost, abandoned, or otherwise discarded (NOAA 2020). Derelict crab traps are a common type of DFG that are found globally and responsible for significant ecological and economic impacts (Arthur et al. 2020). These crab traps are often lost when the lines attaching the traps to a float are broken by wave action or being run over by propellers, which makes the now unmarked traps difficult to recover. Posadas et al. (2021) documented that shrimpers most often deal with derelict crab traps compared to other types of marine debris and DFG. Arthur et al. (2020) estimate that about 25% of all crab traps in the Mississippi, Louisiana, and Alabama blue crab fisheries are derelict. The Mississippi Sound has an estimated 22,000 actively fished crab traps in the state's fishery, and nearly 5,500 derelict crab traps are produced annually while Louisiana has an estimated 188,000 derelict crab traps and Alabama has over 8,000 derelict crab traps annually.

Qualitative studies of Mississippi shrimpers have shown they frequently encounter marine debris, mostly DFG, and it has significant impacts on their operations, indicating that marine debris has a large impact on the industry (Posadas et al. 2021). However, no paired quantitative estimate of marine debris distribution and direct economic impact on the commercial shrimping industry has occurred. As the amount of marine debris increases around the world, its impacts are becoming increasingly apparent. The economic state of the Gulf Coast is heavily dependent on the health of fisheries in the Gulf of Mexico. This fragile ecosystem and economy have suffered tremendously in recent decades from natural and anthropogenic disasters. Studying the distribution and effects of marine debris on the commercial shrimping industry is important to understand and potentially manage yet another stressor facing this industry.

To estimate the quantitative impacts of marine debris on the commercial shrimping industry, this study was designed with specific objectives to (1) characterize the distribution of marine debris that shrimpers encounter during routine fishing operations in the north-central Gulf of Mexico, (2) characterize the abundance and diversity of marine debris that shrimpers encounter, (3) analyze the direct economic impact marine debris has on the Mississippi commercial shrimping industry, and (4) analyze the differences in impacts based on the type of gear used. We hypothesized that (1) there would be higher concentrations of marine debris encounters near the shoreline, (2) plastics would be the most frequently encountered type of marine debris, (3) marine debris would have a negative economic impact on the shrimping industry, and (4) the impacts will be greater with skimmers than otter trawls. Increased knowledge on the types and distribution of marine debris can support the need for benthic debris-focused clean-ups, and knowledge on how marine debris impacts the Mississippi commercial shrimping industry can be used to help shrimpers make informed decisions on the type of gear used.

2. Methods

2.1 Shrimper recruitment

This study focused on the shallow water fishery; captains of bigger offshore/" freezer boats" were not invited to participate in this study. Forty-four (44) shrimpers in Mississippi (36% of the state's fleet) were surveyed in late 2018 to gather location, vessel and gear characteristics, fishing effort, and to gauge interest in participating in an incentivized data collection program. This survey was approved by the Institutional Review Board in 2019 (MSU IRB-18-533) (Posadas et al. 2021). From the participants that expressed interest in participating in an incentivized data collection study, we selected twenty (20) that represented a diverse and representative 16% of all registered shrimpers in the state. They were chosen based on the length of their boat, the type of fishing gear used (e.g., skimmer, otter trawl, and others), which coastal county their boat resides in, and fishing effort (i.e., the number of reported trips in 2018). Shrimpers that completed the data collection procedures for this study were provided a stipend of $300 (USD) per month from July to September 2020 and $500 (USD) per month from October to December 2020 (i.e., $2,400 (USD) per shrimper over the shrimping season). Compensation was based on participation and the submitted logbook entries, not on the number of marine debris encounters documented in the logbook.

2.2 Data collection

Shrimpers were asked to document fishing experiences to accurately describe the amount of marine debris and the direct impacts marine debris has on the shrimping industry (Appendix1). A similar study was done in 2019 to obtain daily estimates of marine debris encountered by shrimpers, and the logbook used for this study was adapted from the preliminary results of that study. Twenty (20) shrimpers were offered $300 a month to participate in the 2019 economic impact study. Shrimpers were asked to fill out a daily summary at least 7 days a month to estimate the economic impacts marine debris had on the commercial shrimping industry. Shrimpers documented the number of tows, length of tows, the weight of catch and time lost due to marine debris, and perceptions of their catch of the day and damage caused by marine debris. While we chose to repeat the study and adapt the logbook from daily summaries to individual tow logs, we were able to compare the results of this study to those of the 2019 study.

Each shrimper who signed up to participate in this study was trained individually to correctly document their fishing experiences in the logbook. As shrimpers registered for the program, they were given the option to document their experiences in real-time either on paper or in the corresponding survey created on Survey123 by ArcGIS. Those that were done on paper were entered into the online survey afterward. When a marine debris encounter did occur, they were asked to identify it and record potential impact data (described later). The types of marine debris were later categorized based on a general list from NOAA Marine Debris Program. Shrimpers were also asked to document their marine debris encounters by taking and submitting a photo; a random subset of these photos was taken to validate the marine debris encounters results. Each logbook reported data associated with every tow completed over the 2020 shrimping season (e.g., July through December). The full logbook is included as an appendix (Appendix 1); however, specific fields from the logbook are listed below:

- Specific times fishing nets were placed in the water and removed
- General location fished specified by gridded map (Figure 1)
- The types of marine debris encountered (e.g., plastic, fishing gear, metal, etc.)
- The estimated amount of catch lost due to encountering marine debris (pounds)
- The estimated amount of fishing time lost due to encountering marine debris (minutes)
- The damage caused to fishing gear/vessel by marine debris (e.g., torn net, tangled motor, etc.)
- The estimated cost of the damage that occurred ($)

2.3 Analyses

2.3.1 Spatial Distribution Analyses

While shrimpers reported location information within individual cells based on the grid map, these cells were grouped into 9 larger fishing areas for spatial analysis (Figure 2). While it was important to group the grid cells as evenly as possible, the fishing areas were grouped by distance from shore and numbered northwest to southeast. An additional factor that was considered when creating the fishing zones was where the fishermen would logically fish during a single day of fishing. While the area of the fishing zone was considered and maintained by grouping 8 grid cells into each zone, the shape of each zone differed from one another. Shrimpers are restricted from fishing within half a mile (0.8 KM) of the shoreline; the nearshore study areas have been designated to include areas 1, 2, 4, and 9 while the offshore study areas include 3, 5, 6, 7, and 8. Some surveys documented that multiple areas from the grid map were fished. For these, the northwest quadrant was chosen to use for both spatial and economic impact analyses.

Using the Euclidean Distance (883 meters; generated from the average distance of marine debris encounters), a nearest neighbor analysis (Aldstadt & Getis 2002) was used to evaluate the spatial distribution of marine debris encountered by shrimpers. The default search area was used to encompass all marine debris encounters without excluding those data points on the peripheral or over-extending the search area.

The Shapiro-Wilk normality test was used to assess the assumption of nonparametric data distribution (Yap & Sim 2011). The Kruskal- Wallis rank-sum test (Smalheiser 2017) was used to determine the probability of encountering marine debris and trends in abundance and diversity of marine debris for each of these 9 study areas. Using the Euclidean Distance, the nearest neighbor analysis (Aldstadt & Getis 2002) was used to evaluate the spatial distribution of marine debris reported by shrimpers. The default search area was used to encompass all marine debris encounters. Analyses with significant results were then applied to ArcGIS to create a series of choropleth maps showing the probability of marine debris encounters using base maps derived from ESRI.

2.3.2 Economic Impacts Analyses

The logbooks kept by shrimpers during the 2020 season did not account for the weight of shrimp caught per tow; because of this, data from 2019 was used in the formula for sales lost due to fishing time lost due to marine debris encounters. Sales lost due to fishing time lost during marine debris encounters were calculated by multiplying the 2020 fishing time lost per tow from the logbooks by the 2019 average catch per minute, 0.364 kg (± 0.395), and the 2019 average dockside price per kilogram ($4.53 (USD)) (EPA 2021).

Due to lack of normality, non-parametric tests were used (e.g., Kruskal-Wallis and Dunn's post hoc test) to assess marine debris' impacts. To assess the effect of fishing location (n=9) and month (n=6) on the response variables of pounds lost, time lost, damage costs, and cumulative direct economic impact, multiple Kruskal- Wallis Rank Sum tests were conducted following the procedures of Queen and Keough (2002). Each Kruskal- Wallis test assessed the effect of fishing location and month on an individual response variable (i.e., pounds lost, time lost, and damage costs) across all the records (with and without marine debris encounters) and separately for records with marine debris encounters (i.e., 2 separate ANOVAs for each response variable). If the location was significant, but the month and the interaction between location and month were not, dates were pooled for Dunn's post hoc comparisons among locations. If a significant interaction between location and month occurred, or location and month were both significant, but the interaction was not, post hoc comparisons were done on each date separately.

3. **Results**

3.1 Abundance, Diversity, and Distribution of marine debris encountered by shrimpers

This study is only focused on the type and amount of marine debris that shrimpers encounter during their regular fishing experiences. The participating fishermen (20) submitted a total of 1,067 tow records. However, 897 tow records were used for data analysis; 170 were excluded because they were either submitted for dates outside of the range of the study (July 2020- December 2020), missing information, or were not representative of a single tow (> 4 hours). Out of the 897 tows, 218 (24%) reported encountering marine debris; however, 50 (5.8%) of those encounters were attributed to organic materials, such as vegetation, which was not a focus of this study, and were excluded from the rest of the analyses.

Marine debris encounters varied by location (Kruskal-Wallis Rank Sum Test – $p = 0.010$) with the highest chance of marine debris encounters occurring in Area 8 (Figure 3). Dunn's post hoc tests indicated that the probability of encountering marine debris in Area 2 was very low; with Areas 2 and 6 ($p = 0.040$) and Areas 2 and 8 ($p = 0.030$) being significantly different from each other. Nearest neighbor tests showed that the observed clustered pattern in marine debris was not random (nearest neighbor ratio = 0.317; $p < 0.001$), which could indicate overarching anthropogenic and environmental drivers that influence these patterns. Marine debris encounters also varied by month (Kruskal-Wallis Rank Sum Test – $p < 0.001$). When comparing the number of tows per month and the number of marine debris encounters per month, the highest percentage of encounters occurred in November (37%) and the lowest occurred in September

(12%) (Figure 4). Dunn’s post hoc comparison showed that 3 comparisons were significant (e.g., July and September $p = 0.004$, August and November $p = 0.023$, and September and November $p < 0.001$; Figure 4).

Overall, shrimpers reported encountering marine debris on 19% of tows. The dominant type of debris encountered by shrimpers was reported to be derelict crab traps (79% of the tows with marine debris encounters) followed by other types of fishing gear (5%) which include fish attracting devices (FADs), fishing poles, and fishing nets; single-use plastics (5%); and unknown trash items (4%; Figure 4). Generally, the assemblage of marine debris encountered was similar in each area (Kruskal- Wallis Rank Sum Test – $p = 0.430$) but varied by month (Kruskal-Wallis Rank Sum Test – $p = 0.007$). However, that monthly result was driven by the difference in marine debris assemblage between October and November (Dunn’s post hoc test- $p = 0.019$) with all other monthly pairwise comparisons showing no statistical difference ($p > 0.050$; Figure 4).

The pattern of marine debris encounters was heavily influenced by the type of fishing gear (Kruskal-Wallis Rank Sum Test – $p = 0.002$). The two distinct gear types used were skimmer (29% of all reported tows) and otter trawls (52% of all reported tows). The remaining 19% of tows reported using either both types of gear or other, unidentified gear. The difference in the likelihood of marine debris encounters between these two dominant gear types was significant. Eighty-six (86) of Skimmer trawl tows (33%) reported encountering marine debris, and 59 Otter trawl tows (13%) reported encountering marine debris (Kruskal-Wallis Rank Sum Test – $p < 0.001$). The probability of marine debris encounters between the two gear types also had a spatial variation (Kruskal Wallis Rank Sum Test- p-value < 0.001; Figures 5 and 6). The use of skimmers resulted in more marine debris encounters in Area 8 while the use of otter trawls resulted in more marine debris encounters inshore and mostly in Area 4. Additionally, the types of debris caught by these two gear types were different (Kruskal Wallis Rank Sum Test – p < 0.001; Table 1). Skimmers caught both more and a wider variety of marine debris than otter trawls.

3.2 Direct economic impacts

Of the 897 tows analyzed, shrimpers reported a direct economic impact of marine debris (i.e., lost fishing time, lost catch, and/or gear damage) for 10% of them. Fishermen reported that 56% and 54% of all marine debris encounters resulted in lost time and catch, respectively, whereas gear damage was only reported for about 7%. Because damage to gear occurred less frequently, lost fishing time and catch were more impactful than gear damage when analyzing all tows and marine debris encounters only (Figure 7; Table 2). Overall, shrimpers reported losing between 0 and 240 min, 0 and 68 kg of shrimp catch, and $0 and $200 (USD) in gear damage per tow due to marine debris.

The length of tows for each gear type was not affected by the marine debris encounter (Figure 8; Kruskal- Wallis Rank Sum Test – p = 0.221). However, the impact of marine debris on lost fishing time (Kruskal-Wallis Rank Sum Test – p < 0.001) and lost catch (Kruskal-Wallis Rank Sum Test – p < 0.001) was heavily influenced by the gear type used (Figure 9). Because gear damage costs did not occur frequently, it did not show an influence of gear type (Kruskal- Wallis Rank Sum Test – $p = 0.466$).

Overall, there were 79 and 56 marine debris encountering tows reported for skimmer and otter trawls respectively (Table 1); however, some tows resulted in multiple types of marine debris caught. Of the marine debris encounters using skimmers, there were 7 tows where multiple debris items were caught, and of the otter trawls, there were 3 tows where multiple debris items were caught (Table 1). While skimmer trawls were over 2 times more likely to encounter marine debris than otter trawls (31% vs. 13% encounter rate per tow), otter trawls accounted for the costliest marine debris encounters. Of those marine debris encounters with skimmers, only 19% reported lost catch and 24% reported lost fishing time due to marine debris. Conversely, over 88% and 86% of otter tows with marine debris encounters reported lost catch and fishing time respectively. Mean catch lost when marine debris was encountered was nearly 15x greater for otter trawls with marine debris encounters (14.23 kg per tow) than skimmer trawls (1.61 kg per tow; Figure 9). Time lost showed a nearly identical pattern with reported means of nearly 28 min and 8 min per tow dealing with marine debris for otter and skimmer trawls respectively (Figure 9).

When analyzing all tows (i.e., with and without marine debris encounters), shrimpers lost an average of 4.61 (± 15.33) minutes removing and disposing of marine debris and lost an average of 2 (± 6.42) kg of shrimp per tow. These losses lead to an average of $16.67 (± $51.23; USD) lost in direct sales per tow. The cost of damage is considered a labor income loss, and while not as frequent, an average of $1.30 (± $14.35; USD) per tow was lost due to damage to fishing nets due to encounters with marine debris. When only considering tows with marine debris encounters, shrimpers lost an average of 18.21 (± 29.13) minutes and 7.88 (± 11.3) kg per tow, increasing the average direct sales lost per tow to $65.67 (± $91.55; USD). The rate of marine debris causing damage to the fishing nets could result in an average of $6.37 (± $31.76; USD) per tow due to repair costs (Table 2).

4. Discussion

This study is the first to our knowledge to quantify the distribution and types of marine debris encountered by commercial shrimpers and their economic impact, and to ensure that the logbook results would be an accurate representation of the debris encountered by shrimpers, payments were based on logbook submission and not based on marine debris encounters logged. Posadas et al. (2021) gathered fishermen's knowledge and perceptions of the impacts of marine debris and analyzed the results from the preliminary survey used to select fishermen for this study. Many of the fishermen who participated in the 2018 qualitative survey participated in the data collection program for this study. This survey assessed the perceived frequency and impacts caused by marine debris in 2018. Ninety-eight (98%) of shrimpers reported that they encountered marine debris during their fishing trips (i.e., a round trip of departure and return to harbor) with 85% encountering it frequently, and most shrimpers indicated reduced catch (80%), lost fishing time (82%), and/or vessel repairs (75%) due to marine debris (Posadas et al. 2021). Similarly, the shrimpers who participated in this study reported making an average of 6 tows per day and accurately estimated that 19% of all tows encountered marine debris. Shrimpers who participated in the qualitative survey reported that crab traps and other abandoned fishing gear were the most common and most destructive types of marine debris encountered (Posadas et al. 2021), which agreed with the results of this study. Although we assumed that plastics would be the most encountered type of marine debris in our hypothesis, logbook results showed that derelict crab traps accounted for 79% of marine debris encounters followed by other types of derelict fishing gear (DFG) in the Mississippi Sound and the north-central Gulf of Mexico.

The probability of shrimpers encountering marine debris was higher throughout the northern study areas, confirming our hypothesis that marine debris encounters would occur more often near the shoreline; however, marine debris encounters also varied by location with the highest chance of marine debris encounters occurring offshore of Biloxi Bay. The mouth of Biloxi Bay and the offshore waters are located just south of Jackson County, whose shrimpers had the highest participation rates. Additionally, blue crab (*Callinectes sapidus*) fishing is also an important industry for the MS Gulf Coast, and no regulations are restricting where crabbers can drop traps. As of 2018, there were 129 registered crabbers in MS. The highest percentage of the registered crabbers was in Jackson County; with 47 registered crabbers, the county made up 36% of all crabbers in MS. Therefore, the higher number of crabbers losing traps in this area could explain a higher probability for shrimpers to encounter marine debris in the waters offshore of Jackson County.

While July through September is generally the peak of the shrimping season (Posadas et al. 2021), the logbook submissions did not peak until October. The onset of "shelter in place" orders due to the COVID-19 pandemic stalled fishing efforts and logbook participation at the beginning of the season which started in June 2020. A general increase in fishing efforts and additional participating fishermen led to a peak in logbook submissions in October. Following the "shelter in place" orders, fishermen dealt with an incredibly busy hurricane season with 8 tropical cyclones making landfall along the Gulf Coast (NOAA 2021; Moore 2020). Hurricane Laura made landfall in Louisiana in late August, Hurricane Sally made landfall near Gulf Shores, Alabama in mid-September 2020, and both Hurricane Delta and Zeta made landfall during October in Louisiana with Zeta passing along coastal Mississippi (NOAA 2021). These hurricanes brought storm surges, winds, and rain that may have moved and/or created marine debris throughout the study areas. Additionally, the higher tides allowed for shrimpers to fish in areas that were previously too shallow to reach. Peaks in marine debris encounters during October could be a result of the areas that were fished were likely littered with marine debris that accumulated over long periods.

There was little diversity in the type of marine debris that was encountered throughout the entire study area and a clustered pattern was observed. Crabbers use metal traps that sit on the seafloor with a buoy attached to mark their location. To increase productivity, crabbers typically drop their traps near each other (Guillory et al. 2001; Arthur et al. 2020); resulting in the clustered pattern observed with the nearest neighbor analysis. These traps are not extremely mobile except for being dragged by a boat's propellors or strong storm surges affecting the currents and dragging them across the seafloor (Guillory et al. 2001), and once crab traps are abandoned or lost at sea, they are considered marine debris (Arthur et al. 2020). Other types of debris encountered included tires, housing or construction materials, single-use plastics, fishing gear, clothing, and rubber material.

Like the results of this study, Posadas et al. (2021) indicated that marine debris has higher impacts on reduced fishing time and catch than gear damage. This study indicated that 56% and 54% of marine debris encounters reported lost time and catch whereas only 7% of marine debris encounters reported direct gear damage, confirming our hypothesis that marine debris would have negative economic impacts on the commercial shrimping industry. However, the impact of marine debris on lost fishing time and lost catch was heavily influenced by the gear type used.

The Mississippi shrimping industry is managed by the setting of seasons based on the average size of white (*Litopenaeus setiferus*), and brown shrimp (*Farfantepenaeus aztecus*), fishing locations that vary throughout the season, tow times based on boat size, and the enforcement of attaching a turtle excluder device (TED) to gear (MDMR 2021). The two most common types of trawls used in Mississippi are otter and skimmer trawls. Otter trawls are towed directly behind the boat and must be taken completely out of the water when marine debris is caught (Coale et al. 1994). Skimmers are mounted on a frame and pushed along either side of the boat, fishing the entire water column. Individually, the skimmer nets are about half the width of the otter trawls; however, because two skimmer nets are used at the same time, the two types of gear cover about the same area while fishing (Coale et al. 1994). Through conversations with the shrimpers, the size of the mesh used for nets does not depend on the type of gear used, but it does depend on the targeted shrimp species; shrimpers use nets with a mesh size between 35-mm and 90-mm. Unlike we anticipated in our hypothesis, the difference in the likelihood of marine debris encounters between these two gear types was significant with over 31% of the skimmer and only 13% of otter tows reporting encountering marine debris.

Marine debris encounters are not a new phenomenon for shrimpers, so shrimpers have already adjusted their schedules to deal with the consequences. Due to gear types, shrimpers encounter benthic marine debris, which sits on the seafloor, more often than encountering floating marine debris (Spengler & Costa 2008). On the Gulf Coast, benthic marine debris mostly consists of DFG, including crab traps, which our results show is the likely cause of the most impactful marine debris encounters for shrimpers. There was an average loss of 2 (± 6.42) kg of catch, 4.61 (± 15.33) minutes, and $1.30 (± $14.35; USD) costs in gear damage per tow; these collectively corresponded to about $16.66 (± $51.21; USD) per tow in direct losses per tow. Ten percent (10%) of all tows result in lost time and/or catch; this leads to an average of just 2.77 minutes and 1.2 kg lost per day. These losses would not lead to fewer tows per day but may result in longer hours on the water. This way overall catch is not reduced. When only considering tows with marine debris encounters, shrimpers lost an average of 18.21 (± 29.13) minutes, 7.88 (± 11.3) kg per tow, and $6.37 (± $31.76; USD) in gear damage per tow.

Although the most frequently fished area reported for both types of gear was near the mouth of Biloxi Bay, the probability of marine debris encounters between the two gear types also had a spatial variation. The use of skimmers resulted in more marine debris encounters offshore of the mouth of Biloxi Bay while the use of otter trawls resulted in more marine debris encounters inshore and mostly just off the coast of Harrison County. A possible explanation for these differences is skimmers fish the entire water column while otter trawls only fish along the seafloor. Coale et al.'s (1994) study comparing rates of bycatch between the two types of gear, showed that skimmers were unable to fish in waters with greater depths than 3.7 m while the otter trawls skim the seafloor. The more frequent and wider variety of marine debris encounters with skimmers may be a result of these nets being susceptible to both benthic and floating debris.

Overall, shrimpers do an average of 6 tows per day when fishing (EPA 2021); at the current rate of marine debris encounters (19% of tows) this would equate to $100.02 lost per day. These shrimpers reported fishing an average of 11 days per month (Posadas et al. 2021) during the shrimping season (June- December), so these marine debris impacts can be extrapolated to a total of $6,601.27 (2020 $USD) lost each season. There were 120 registered shrimpers in the State of Mississippi during 2020 (MDMR 2021), so assuming each shrimper encounters the same level of marine debris as encountered in this study, the total annual negative direct economic impact on the Mississippi shrimping industry is nearly $800,000 per year. This impact is significant when considering the total dockside sales of Mississippi commercial shrimpers in 2019 was only $15 million (Posadas 2021).

The marine debris recorded in the data collection is likely an underestimation of the marine debris in the Mississippi Sound. EPA's Gulf of Mexico Program funded a 2-year collaborative cleanup effort specifically incentivizing commercial shrimpers to remove derelict crab traps from the seafloor. Before this program, shrimpers often tossed the derelict crab traps caught back overboard rather than removing and properly disposing of them. Between 2019 and 2020, nearly 2,300 traps were removed from the waters (Sartain et al. 2021), so much of the marine debris that could have impacted fishing efforts had already been removed. Another limitation to this study is that shrimpers were not asked to report catch for each tow. Instead, shrimpers were asked to estimate the weight of shrimp catch reduced per tow using their experience and referencing other tows from that day. Because these estimates of lost catch and lost fishing time were subjective to the shrimper, the economic impacts discussed should also be considered estimates; however, the shrimpers have had lifetimes' worth of experiences, and we trusted the judgments made throughout this study. Additionally, the quantitative estimates made in this study aligned with the perceptions of marine debris and its impacts analyzed in the 2019 study. It's important to note that this survey was done during real-life fishing hours with minimal compensation relative to the effort of shrimpers. Therefore, the logbook was developed to be as simple and convenient as possible to get accurate direct impacts.

The expenses caused by marine debris could become critical for an industry that is already subjected to a variety of stressors such as an aging workforce and increasing frequencies of natural and anthropogenic disasters. As development and litter increase worldwide, the marine debris crisis is expected to escalate as well (Kaza et al. 2018).

For shrimpers, damaging encounters with marine debris will likely escalate. Along with potentially increasing lost sales from lost fishing time and catch and costs of damage caused by marine debris, shrimpers must also balance rising costs of marine diesel (Seba 2019) and the falling prices of both dockside and wholesale prices for shrimp (Posadas 2020). The Gulf States have provided over 86% of commercially caught wild shrimp for the nation (Posadas 2020). Compared to the other Gulf States, Mississippi's shrimping industry is relatively small, and Mississippi has had the least amount of derelict crab traps. The impacts of marine debris paired with natural and anthropogenic disasters, rising fuel costs, and falling prices of wild shrimp could be crippling for the industry throughout the region.

5. Conclusion

This study is the first to quantify the impacts of marine debris on the commercial shrimping industry. However, Arthur et al. (2020) analyzed the benefits of a derelict crab trap cleanup along the Gulf Coast. This study concluded the removal of these traps would be beneficial for both the blue crab and finfish fisheries with additional benefits for the economy, marine mammals and sea turtles, and boating traffic (Arthur et al. 2020). Shrimpers and crabbers generally fish in the same areas, so when traps become unmarked or derelict, they are likely to sit on the seafloor until a shrimping trawl picks them up (Guillory et al. 2001).

The higher number of marine debris occurrences per tow documented in October and November suggest that distribution and patterns of encountering marine debris could have been influenced by hurricanes in the Gulf of Mexico during the study period.

Additionally, the type of gear used influenced the type and magnitude of debris caught as well as the economic impact. To alleviate and prevent these marine debris encounters, shrimpers may want to consider the type of gear that they choose, and a benthic marine debris-focused cleanup should be done before the start of the hurricane/shrimping seasons each year (Arthur et al. 2020).

Data Availability Statement:

All data associated with this project is formatted and ready for upload into the Mississippi State University Institutional Repository. Upon acceptance of publication, all data will be uploaded to the repository and made fully available.

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Figures

Figure 1 Grid map used by shrimpers to document fishing area. Shrimpers used the map to identify the general location in which they fished for each tow reported. US map inset was not in the original shrimper form but was added here to represent a general geographic area of the study.

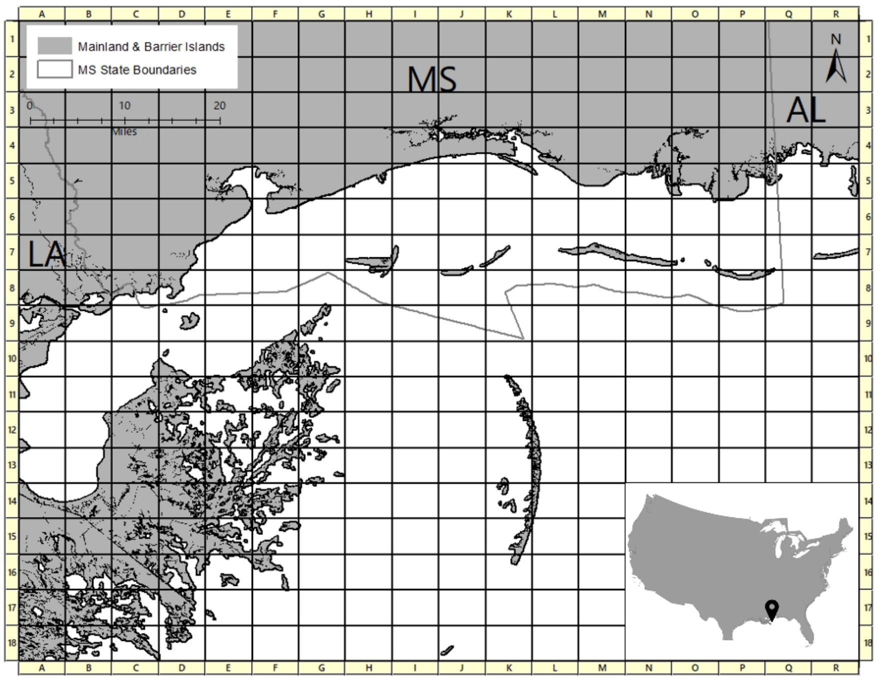


Figure 2 Fishing zones created from the documented grid cells by shrimpers. Nine study areas were created for data analysis.

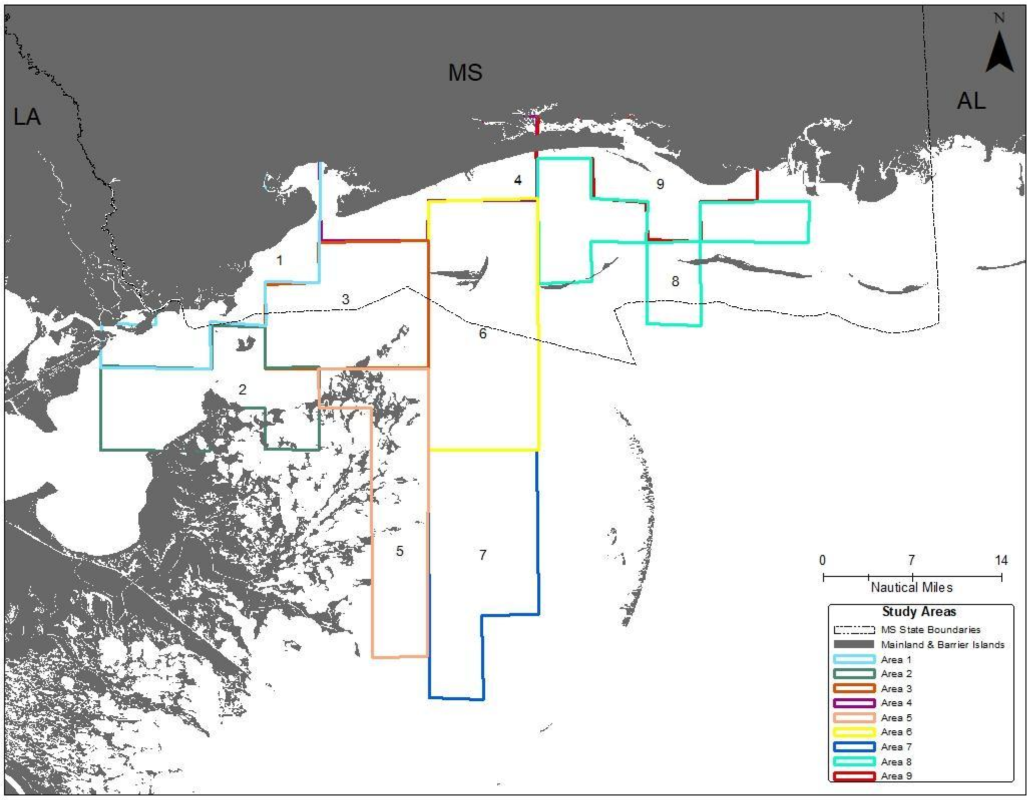


Figure 3 The probability of encountering marine debris reported by shrimpers.

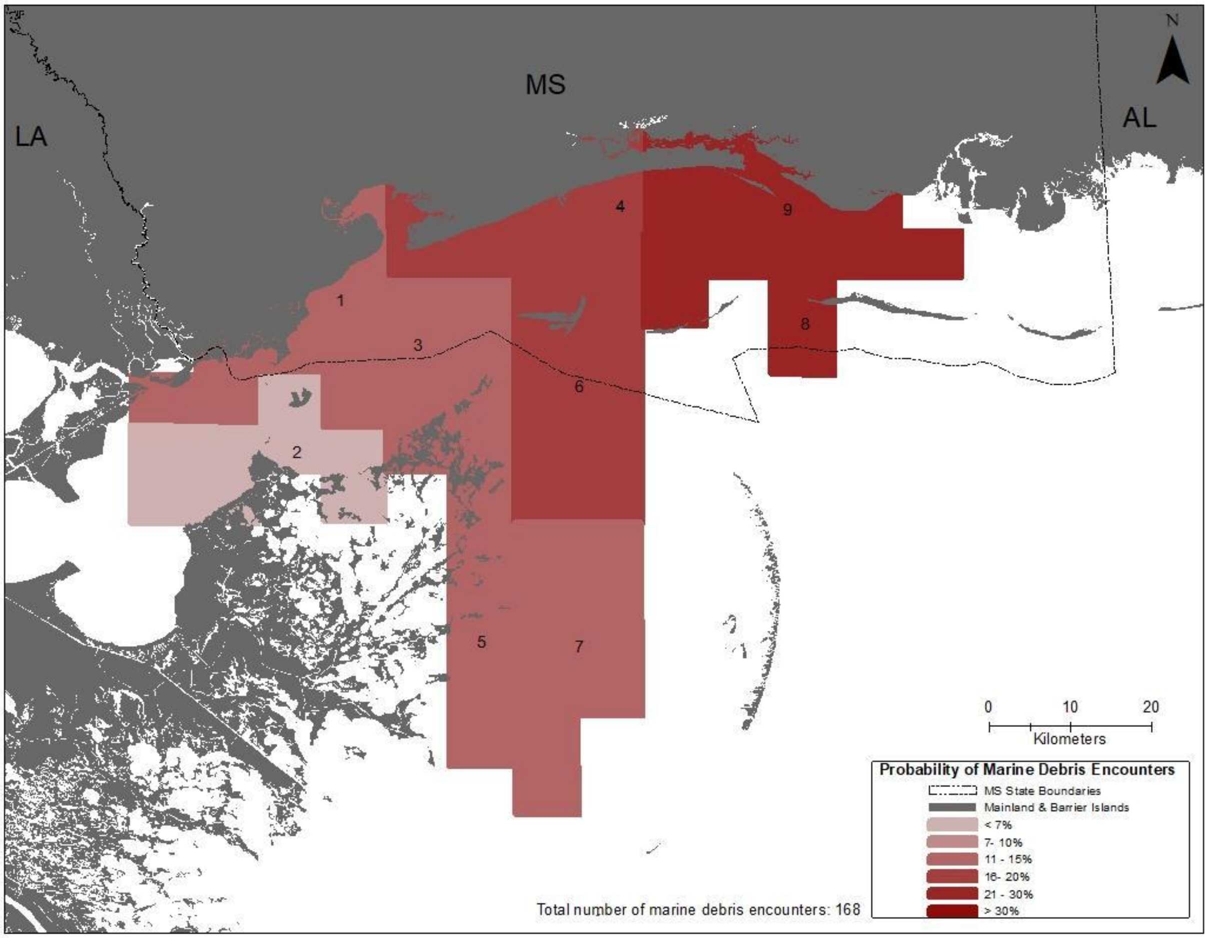


Figure 4 Frequency of marine debris encounters by marine debris type on a per tow basis each month.

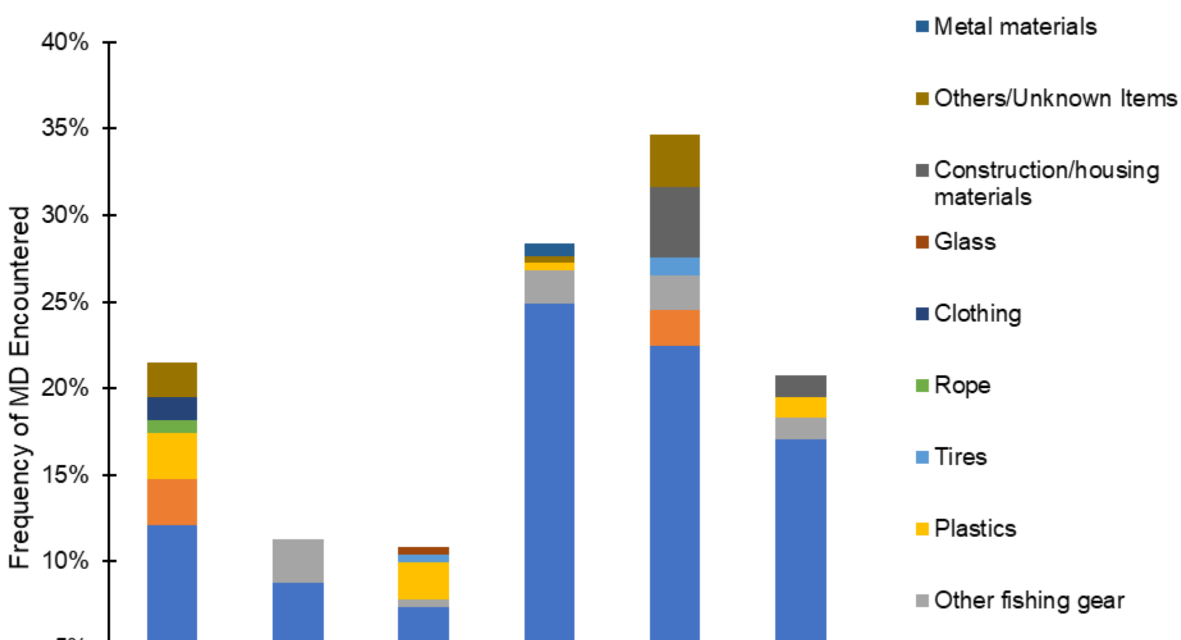


Figure 5 Map of spatial probability of encountering marine debris using a skimmer.

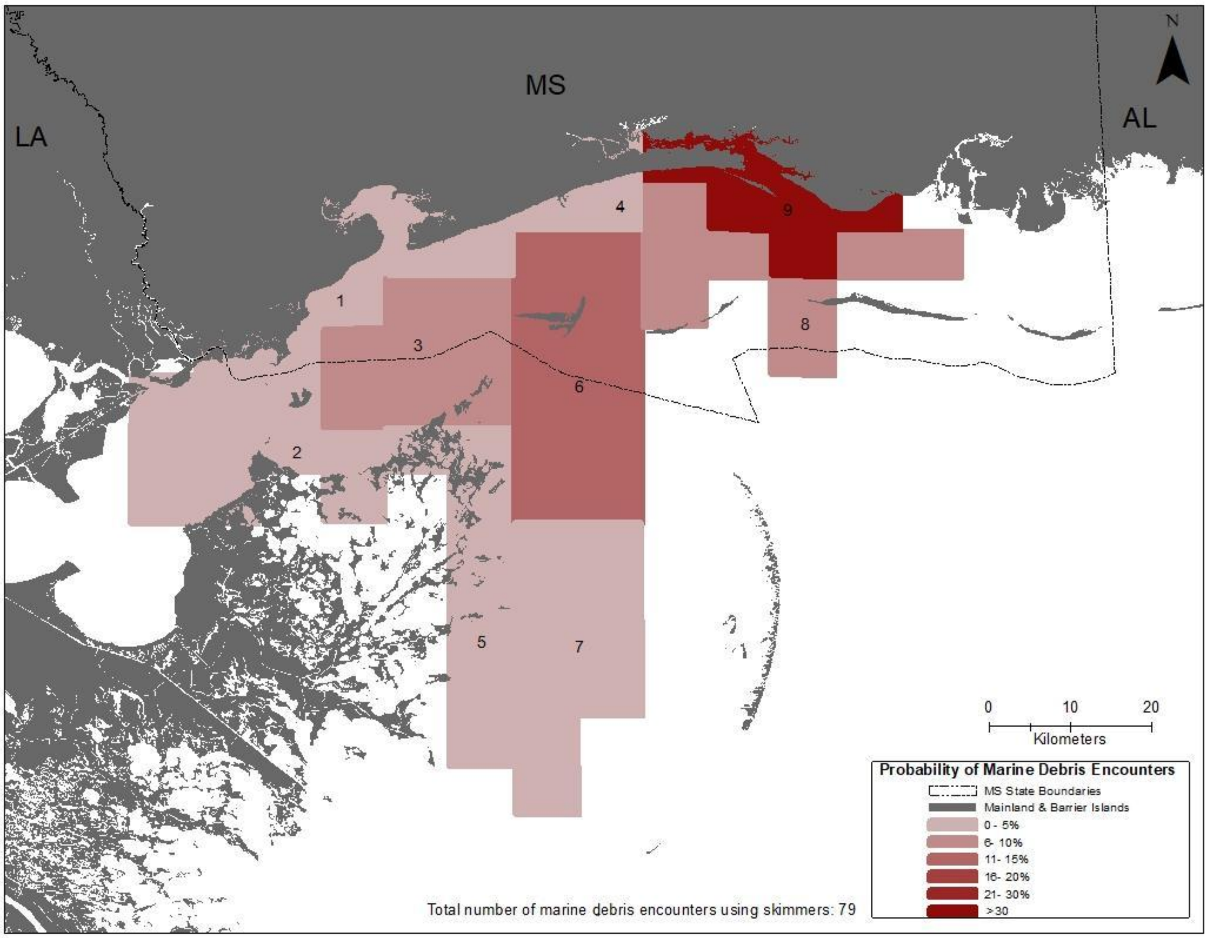


Figure 6 Map of spatial probability of encountering marine debris using an otter trawl.

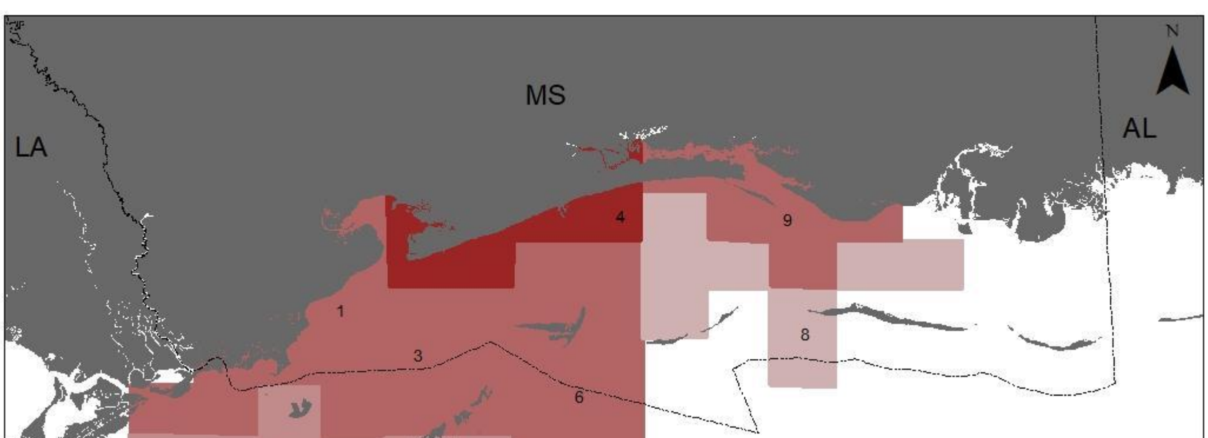


Figure 7 Comparison of the observed impacts when analyzing only marine debris encounters.

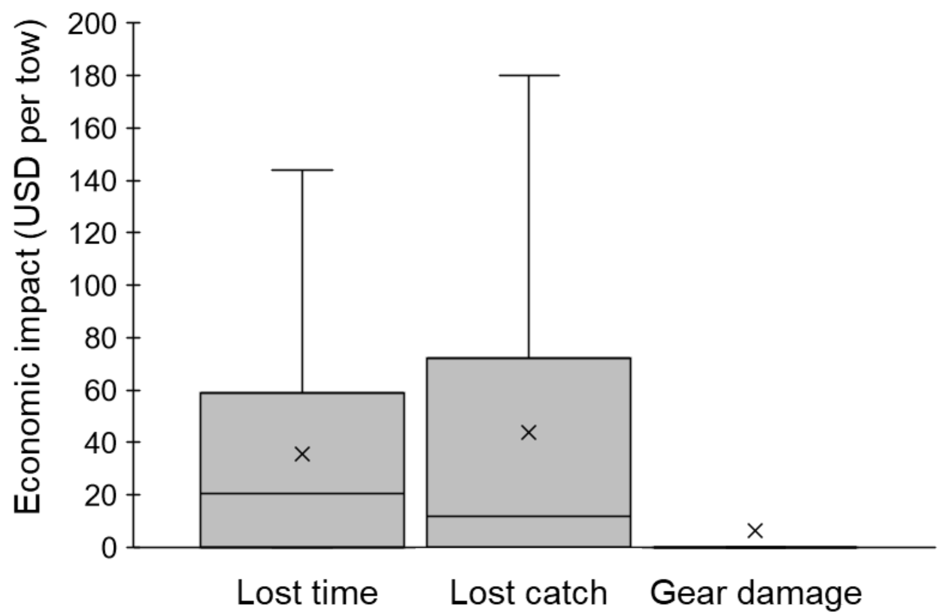


Figure 8 Comparison of the length of tows for each gear type with and without marine debris encounters.

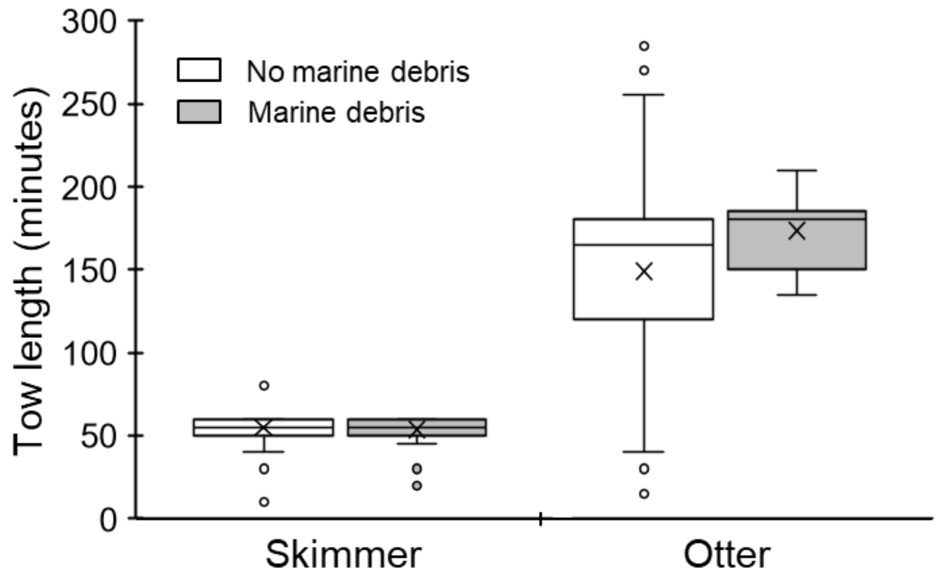
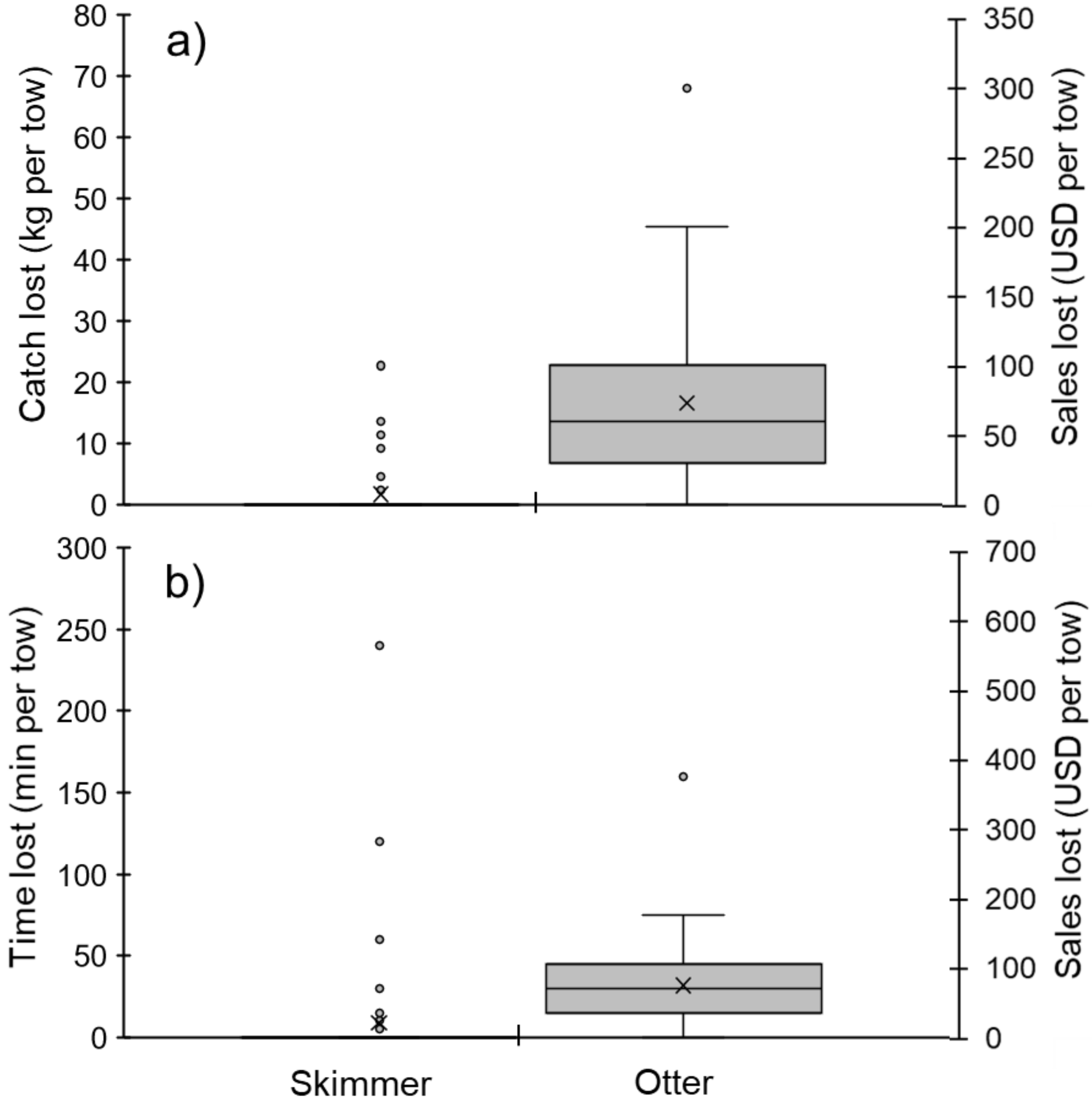


Figure 9 Comparison of impacts caused by marine debris for both gear types (skimmer and otter trawls).



Tables

Table 1

Types of Marine Debris Caught by Gear Type

	Otter Trawls	Probability of Occurrence	Skimmers	Probability of Occurrence
Derelict Crab Traps	46	10%	65	25%
Wooden Materials	1	0%	0	0%
Other Types of Fishing Gear	2	0%	5	2%
Plastics	2	0%	7	3%
Tires	1	0%	0	0%
Rope	0	0%	1	0%
Clothing	0	0%	2	1%
Glass	0	0%	1	0%
Construction/Housing Materials	4	1%	0	0%
Others/Unknown Materials	3	1%	3	1%
Metal Materials	0	0%	2	1%

Marine debris caught and the probability of occurrence. Amount of each type of marine debris documented by shrimpers and the probability of encountering each type based on the type of gear used.

Table 2

Impacts of Marine Debris at each Percentile

		25%	50%	75%	Mean
Kg Lost	All Tows	0.00	0.00	0.00	2.01
	MD Encounters	0.00	4.54	13.04	7.88
Fishing Time Lost (minutes)	All Tows	0.00	0.00	0.00	4.61
	MD Encounters	0.00	5.00	30.00	18.21
Damage Costs ($)	All Tows	$-	$ -	$ -	$ 1.30
	MD Encounters	$-	$ -	$ -	$ 6.37
Total Sales Lost	All Tows	$-	$ -	$ -	$16.66
	MD Encounters	$-	$29.79	$110.96	$65.63

Impacts marine debris had on shrimpers. The impact marine debris had on shrimpers per tow including kilograms lost, fishing time lost, total sales lost, and damage costs.

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Author Contributions

Alyssa Rodolfich: Conceptualization, Methodology, Investigation, Writing- original draft, writing- review, and editing. **Eric L. Sparks:** Conceptualization, Methodology, Investigation, Resources, Project administration, Funding acquisition, Writing- review, and editing. **Benedict C. Posadas:** Conceptualization, Methodology, Investigation, Writing- review, and editing. **John Rodgers III:** Conceptualization, Methodology, Investigation, Writing- review, and editing. **Ryan Bradley:** Conceptualization, Project administration, Funding acquisition, Writing- review, and editing. **Caitlin Wessel:** Conceptualization, Project administration, Funding acquisition, Writing- review, and editing.

Appendices

Appendix 1. Logbook used by shrimpers to document fishing tows and marine debris encounters.

	Date (MM/DD/YYYY)	Time IN	Time OUT	General Area (See Grid Map)	Did you encounter marine debris? (Y/N)	What types of marine debris?	How many pounds of catch did you lose?	How much time did you lose handling the marine debris?	Did the marine debris damage your vessel or gear? (Y/N)	What did it damage?	What is the estimated cost of the damage? ($$)	Did you take a picture? (Y/N)
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1. Entry number
2. Date (MM/DD/YYYY)
3. Time IN
4. Time OUT
5. General Area (See Grid Map)
6. Did you encounter marine debris? (Y/N)
7. What types of marine debris?
8. How many pounds of catch did you lose?

9. How much time did you lose handling the marine debris?

10. Did the marine debris damage your vessel or gear? (Y/N)

11. What did it damage?

12. What is the estimated cost of the damage? (USD$$)

13. Did you take a picture? (Y/N)