An Alternate Trawling Method: Reduced Bycatch and Benthic Disturbance Achieved with the Wing Trawling System

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An Alternate Trawling Method: Reduced Bycatch and Benthic Disturbance Achieved with the Wing Trawling System

A Thesis

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in
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by
Geoffrey Udoff
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**Abstract**

The Wing Trawling System (WTS) was tested as an alternative to traditional shrimp capture methods in the Gulf. Compared to an otter trawl, this trawl was conceived to reduce bycatch, retain shrimp catch, and minimize seafloor disturbance. Through seventy-one paired tows, the WTS was assessed against a standard otter trawl. The WTS was found to reduce bycatch by 63-65% and reduce shrimp catch by 30-35%. Additionally, I measured the depth of the scars produced by both trawls and quantified the turbidity of the plumes behind them. The scars left by the WTS and the otter trawl were between 9.9 cm-13.6 cm. The turbidity behind the WTS was 18.6 NTU, while the turbidity behind the otter trawl was 206.8 NTU. In conclusion, the WTS offers an alternative to an otter trawl that reduces bycatch and the impact trawling has on the seafloor but results in a significant amount of shrimp loss.

**Keywords:** Bottom Trawl, Benthic Disturbance, Bycatch Reduction, Otter Trawl, Wing Trawling System
Chapter One

Bycatch Reduction of the Wing Trawling System in Comparison to an Otter Trawl

Introduction

Shrimp trawls have been cited as the number one contributor to global bycatch, accounting for a third of the world’s discards (Alverson, 1994). Bycatch is defined as the capture of non-target organisms in a fishery. In the mid-1900s, fisheries experienced an increase in catch per unit effort that had been linked to technological advances in gear efficiency, leading to over-exploited resources (FAO, 2001). It is likely that this advance also contributed to increases of bycatch, resulting in a need to improve fishing selectivity. In 1969, the issue of excess bycatch in the United States was addressed with the idea of modifying shrimp trawls (High et al., 1969). One of the first net modifications tested in the United States was that of Seidel (1977), who proposed a mesh separator to physically exclude finfish from the net. Following that addition, Watson and McVea (1977) proposed numerous different net modifications in a controlled study including changes to mesh sizes and the shape of the net (Watson and McVea, 1977). Modifications to reduce bycatch either take advantage of fish behavior or physically separate bycatch with a mechanical device (Broadhurst, 2000).

In response to the growing concerns of bycatch and the decline of the sea turtle populations, the National Marine Fisheries Service (NMFS) created the Trawling Efficiency Device or Turtle Excluder Device (TED) in 1980 (Jenkins, 2012) to reduce both sea turtle and finfish capture by using a grid placed in the net to mechanically separate bycatch from shrimp (Watson et al., 1985). TEDs also take advantage of the behavioral differences in fishes and shrimp by creating areas of reduced water flow, facilitating the escape of the better swimming
turtles and fishes (Watson et al., 1985). By 2000, over 40 modifications had been proposed and tested to varying degrees of success to reduce bycatch in shrimp trawls (Broadhurst, 2000). The drive to reduce bycatch from shrimp trawling has been influenced not only by ecological concerns but also by economics. Reducing bycatch from the fishery would increase the value of the shrimp and reduce the amount of time required for fisherman to sort the catch (Brewer et al., 1998; Pascoe and Revill, 2004). Additionally, if bycatch is significantly reduced, the shrimp would not be as crushed or damaged by the presence of finfishes, thereby helping to maintain their integrity and higher market value. Despite these potential benefits, TEDs and other bycatch reduction devices have been met with resistance from fishermen because of the possibility of shrimp loss.

Numerous studies have compared the effect of bycatch reduction devices against industry standards to determine loss of catch (Renaud et al., 1993; Brewer et al., 2006; Krag et al., 2010; Broadhurst et al., 2012). Renaud et al. (1993) tested two different types of TEDs, the Georgia TED and the Supershooter. While testing the TEDs against identical nets without TEDs he found that the Georgia TED reduced shrimp catch by 3.6-13.6%. The Supershooter did not have a significant loss of shrimp. Clark et al. (1991) found that the Georgia TED did not significantly reduce shrimp catch and reduced bycatch by 24%, and in a similar study the Supershooter was found to reduce bycatch up to 16% (Brewer et al., 1998). The TED was also implemented in Australia to determine the possible benefits of excluding turtles. Brewer et al. (2006) found that the TED with and without other bycatch reduction devices resulted in 4.2-6.0% shrimp loss and 7.9-8.0% bycatch reduction; additionally, the exclusion of large rays and sharks was up to 94%. Another bycatch reduction device, the Nordmøregrid was found to reduce bycatch up to 74% with a shrimp loss of 4% (Broadhurst et al., 2012). Bycatch reduction devices have been used in
fisheries outside of shrimp. A haddock fishery in the North Sea was capturing too many cod as bycatch. The solution was to raise the footrope, taking advantage of the cod’s behavior to swim down when it interacts with the trawl. This reduced bycatch by up to 82% with a corresponding loss of between 1-11% of the desired species (Krag et al., 2010). Shrimping communities in the Gulf of Mexico region did not embrace required TED use (Modeberg and Dyer, 1994). Fisherman believed that as little as a 10% reduction in shrimp catch would be enough to make shrimping an unprofitable venture (Mialjevich, 1987). Furthermore, it was noted that in the year following mandatory TED use 27 out of 69 shrimpers in Bayou la Batre, Alabama, were no longer activity shrimping, presumably due to the TED mandate (Modberg and Dyer, 1994). As such, there is a need for continued research into devices that reduce bycatch but retain shrimp catch in the shrimping industry.

Randy Skinner, an Alabama shrimper and inventor of the Wing Trawling System (WTS; Figure 1.1), claims to have invented an alternative to an otter trawl that will reduce bycatch while retaining an equal amount of shrimp. Unlike otter trawl doors that create clouds of displaced sediment herding fishes into the net (Main and Sangster, 1981; Wardle, 1986), the WTS eliminates the doors which could reduce the impact of herding and subsequently reduce bycatch, at the same time eliminating the more extreme benthic scouring caused by the heavy trawl doors. The trawl net associated with the WTS essentially functions the same as that associated with traditional wooden or aluminum otter trawl doors. For both gear types, the net fully opens, and the ground rope skims along the water bottom with a tickler chain located forward of the ground rope agitating the sediment ahead of the net forcing shrimp from the benthos where they are then more easily captured by the trawl. The effective difference between the two methods is the
presence of the trawl doors, which assumedly function in a manner which increases bycatch (Figure 1.2).

**Figure 1.1**: Photograph of the Wing Trawling System (WTS) showing how the trawl net is attached to the 'wing'.

**Figure 1.2**: Diagram of the paired test design with the otter trawl on port side and WTS on starboard side (adapted from Randy Skinner).
Given the potential benefits of the WTS, the overall objective of my research was to determine if the WTS is a viable alternative to a traditional otter trawl with doors. To test the proposed effectiveness of the WTS versus typical otter trawling in reducing bycatch yet retaining shrimp, my specific objectives were:

1. To compare the differences in weight of penaeid shrimp and bycatch captured with the WTS and an otter trawl;
2. To compare differences of shrimp count per 1 kg between the WTS and otter trawl;
3. Assess difference in weight of penaeid shrimp and bycatch captured during the day and night;
4. Compare differences in finfish lengths between gear types; and
5. Assess the affect of abiotic factors on both finfish and shrimp for both gear types

Materials and Methods

Paired Testing

This study took place from August-September, 2015 around the Louisiana Delta and Alabama Coast. A majority of the tows occurred on the southeastern portion of the Louisiana Delta (Figure 1.3). The M/V Apache Rose, a 19.8 m steel shrimp trawler with a 6.7 m beam powered by two 350 hp engines, pulled the WTS and otter trawl simultaneously in a paired test design. The otter trawl was towed on a short block to account for the difference in drag. The WTS was comprised of an 11.582 m wing trawl, 13.716 m two-seam net, and a 1.270 flat bar top-opening TED. The otter trawl was comprised of the same two-seam net and TED, but with 2.438 x 1.016 m wooden doors (Figure 1.4). NOAA divers measured net spreads of both the WTS and otter trawl in June 2015 using a marked cable attached to the last hanging on each end.
of the headrope. The WTS net spread was 10.972 m while the otter trawl net spread was 9.906 m. Headrope height was also measured for each trawl with the WTS measuring 1.219 m and otter trawl 1.280 m. Footrope height off the bottom was also measured for each trawl with WTS and otter trawl footrope heights measured 5.08 cm. Seventy-one tows of 120 ±5 minutes at 2.5 ± 0.5 knots were conducted to replicate commercial fishing conditions. To limit vessel side bias, the number of left and right turns remained equal throughout the trip (Rulifson et al., 1992; Price & Gearhart, 2011). Additionally, after forty-one tows the WTS and otter trawl were switched between the starboard and port sides of the vessel to mitigate for any potential bias associated with net position relative to the vessel. At the beginning and end of each tow, GPS coordinates were recorded so that distance covered could be estimated. Additionally, WindPlot was used to record the boat’s location every 92.6 m during the tow to provide a more accurate measurement of distance covered, and depth was recorded upon deployment and retrieval of the trawl.

Figure 1.3: Sampling locations along the Mississippi River Delta (n = 65) and the coast of Alabama (n = 6).
Similar to the NOAA observer protocol (NMFS, 2010), the total catch of each trawl haul was weighed and separated into four categories consisting of finfish, shrimp, other invertebrates, and debris. Care was taken to ensure that the catch did not mix between trawl types. The catch from each of the four categories was weighed to the nearest 0.01 kg using a TCI Model LPC-4-HS scale. Any organism or item that was too large to be weighed in a basket with the rest of the catch was weighed in a separate basket and the standard length was measured to the nearest mm. After tow #30 the TCI© Model LPC-4-HS scale was damaged by water. Remaining weight measurements were taken on a 20 kg Pesola® scale and weights were measured to the nearest 0.1 kg. As time allowed, the number of shrimp per 1 kg was taken to determine a shrimp count and to assess if the WTS was size selective for shrimp. Also, a point was made to trawl during both the day and night to document diurnal differences in fish and shrimp catches (Helfman,
All shrimp measurements were made after the heads had been removed during processing.

Additionally, 25 tows were subsampled to test the possibility that the WTS selectively captures fishes by length. One shrimp basket (~20 kg) was randomly taken out of the total catch for each gear type. If the total catch was less than one basket the entire catch was sampled. Three species of fishes were chosen, Spot (*Leiostomus xanthurus*), Atlantic Croaker (*Micropogonias undulatus*), and Gulf Menhaden (*Brevoortia patronus*). These species were chosen based on their routine presence in the shrimp trawl. Twenty-five individuals were randomly chosen out of the subsampled basket and measured to the nearest millimeter. Also, when Red Snapper (*Lutjanus campechanus*) and Spanish Mackerel (*Scomberomorus maculatus*) were present in the trawl, all individuals were measured for each gear type. Additionally, abiotic data from surface water samples were measured with a YSI model 85 meter (Yellow Springs Instruments, Yellow Springs, Ohio) prior to each tow and included temperature, salinity, conductivity, specific conductivity, and dissolved oxygen (DO). Finally, although not used for statistical analyses, I noted any rare species or species of interest when they occurred in the catch.

**Statistical Analysis**

The catch was normalized by both distance covered and area swept using the following conversion: catch(kg)/(area swept x distance covered). The WTS covered 13.375 m², while the otter trawl covered 12.680 m². The catch was divided by the normalized ratio, 1 for the WTS and 0.9479 for the otter trawl, and then multiplied by the distance covered. Tows in which shrimp catch was less than 1.5 kg were omitted from the statistical comparison. Tows with such little catch would not yield a fair comparison of the gear. With so few shrimp captured it would...
be difficult to determine if the shrimp were captured by chance or a difference in gear type. Due to the shrimp omissions from the data, finfish, other invertebrates, crustaceans, and debris were analyzed separately with no omissions. Also, some tows were omitted by ordering the catch from high to low and removing excessively high and low catches until equal tows were reached. This process was chosen over random omission, because the resulting data will better represent the performance of the trawls. Due to the nature of the experiment, low and high catches occurred throughout the study that do not reflect the performance of the trawl.

The null hypothesis that no differences exist in shrimp weight, bycatch weight, and shrimp counts between the WTS and otter trawl treatments was tested with paired t-tests ($\alpha = 0.05$). Additionally, a two-sample t-test ($\alpha = 0.05$) was used to assess the influence of time of day (day/night) on shrimp and finfish catch by weight. To determine if the WTS was selectively capturing fishes by length I used a Kolmogorov–Smirnov test ($\alpha = 0.05$). Due to the nonparametric nature of fish length measurement data, this test used ranks and compared the distributions of the fish lengths for each gear type. Finally, multiple linear regressions were performed to determine the affect of surface salinity, turbidity, temperature, DO, and depth on fish and shrimp catch between both gear types. First a saturated model was created, and then the model was reduced stepwise in regards to the lowest Akaike’s Information Criterion (AIC). For this portion of the analysis both trip one and two were combined to bolster that amount of abiotic data available to analyze. Also, these data are not directly representative of abiotic conditions associated with the trawl because they are surface water measurements and testing occurred at the seafloor. The average water depth was 3.04 m, and the maximum depth was 18.6 m. Due to these shortcomings, no interactions were included in the analysis.
Results

Catch comparison

The total catch data between each side of the boat was significantly different for the WTS (n=29, t = -3.0388, p = 0.004; Figure 1.5) and otter trawl (n=29, t = -7.3217, p < 0.001; Figure 1.5) therefore; the data were broken down by trip one (WTS starboard) and trip two (WTS port) for statistical analyses. During trip one, when the WTS was on the starboard side and the otter trawl was on the port side the WTS caught significantly less shrimp (n = 37, t = 4.99, p < 0.001; Figure 1.6) and fishes by weight (n = 39, t = 8.9727, p < 0.001; Figure 1.6). The WTS caught 30% less shrimp and 65% less fish than the otter trawl when it was on the starboard side (Figure 1.7). Shrimp count, other invertebrates, crustaceans, and debris captured did not differ by gear type (Table 1.1). Additionally, catch did not differ between day or night for any of the measured categories when the gear was on the starboard side (Table 1.2). Analysis of shrimp count when the gear was on the port side could not be performed due to lack of data.

Figure 1.5: Total catch of both the otter trawl and the Wing Trawling System (WTS). Normalized catch is the catch/(area swept x distance covered). The WTS and otter trawl switched sides approximately halfway through the experiment. When the WTS was on the port side the otter was on the starboard side and vice versa. The differences in catch between the port and starboard side with the WTS were significant (n= 29, t = -3.0388, p = 0.004). Also the differences in catch between the port and starboard side with the otter trawl were significant (n=29, t = -7.3217, p < 0.001).
**Figure 1.6:** The total shrimp (left) and fish (right) captured while the Wing Trawling System (WTS) was on the starboard side and the otter trawl was on the port side. Normalized catch is the catch (kg)/(area swept x distance covered). The WTS captured significantly less shrimp (n = 37, t = 4.99, p < 0.001) and fishes (n = 39, t = 8.9727, p < 0.001).

**Figure 1.7:** Percent difference of catch between the otter trawl and Wing Trawling System (WTS) for fish and shrimp (right) and crustaceans, invertebrates, and debris (left). Blue is catch when the WTS was on the starboard side and the otter trawl is on the port side. Red is catch when the WTS is on the starboard side and the otter trawl is on the port side.
Table 1.1: Non significant results of t-tests preformed on the WTS when it was on the starboard side.

<table>
<thead>
<tr>
<th>Side</th>
<th>Catagories</th>
<th>n</th>
<th>t</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>WTS-Starboard</td>
<td>Shrimp Count</td>
<td>36</td>
<td>-0.8425</td>
<td>0.405</td>
</tr>
<tr>
<td></td>
<td>Invertebrates</td>
<td>40</td>
<td>0.7408</td>
<td>0.463</td>
</tr>
<tr>
<td></td>
<td>Crustaceans</td>
<td>39</td>
<td>1.2248</td>
<td>0.228</td>
</tr>
<tr>
<td></td>
<td>Debris</td>
<td>40</td>
<td>0.341</td>
<td>0.735</td>
</tr>
</tbody>
</table>

Table 1.2: Results of t-tests for differences in day and night tows. All tests were not significant. Shrimp count when the gear was on the port side could not be tested due to lack of data.

<table>
<thead>
<tr>
<th>Gear Type</th>
<th>Catagories</th>
<th>n</th>
<th>t</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starboard</td>
<td>Fish</td>
<td>24</td>
<td>-0.429</td>
<td>0.672</td>
</tr>
<tr>
<td></td>
<td>Shrimp</td>
<td>26</td>
<td>1.581</td>
<td>0.127</td>
</tr>
<tr>
<td>Otter Trawl</td>
<td>Crustaceans</td>
<td>16</td>
<td>-1.089</td>
<td>0.292</td>
</tr>
<tr>
<td></td>
<td>Invertebrates</td>
<td>18</td>
<td>1.786</td>
<td>0.092</td>
</tr>
<tr>
<td></td>
<td>Shrimp Count</td>
<td>9</td>
<td>-0.630</td>
<td>0.545</td>
</tr>
<tr>
<td>WTS</td>
<td>Fish</td>
<td>31</td>
<td>-0.111</td>
<td>0.912</td>
</tr>
<tr>
<td></td>
<td>Shrimp</td>
<td>29</td>
<td>1.779</td>
<td>0.086</td>
</tr>
<tr>
<td></td>
<td>Crustaceans</td>
<td>17</td>
<td>-0.707</td>
<td>0.489</td>
</tr>
<tr>
<td></td>
<td>Invertebrates</td>
<td>21</td>
<td>1.491</td>
<td>0.151</td>
</tr>
<tr>
<td></td>
<td>Shrimp Count</td>
<td>17</td>
<td>-0.707</td>
<td>0.489</td>
</tr>
<tr>
<td>Port</td>
<td>Fish</td>
<td>24</td>
<td>-0.728</td>
<td>0.474</td>
</tr>
<tr>
<td></td>
<td>Shrimp</td>
<td>22</td>
<td>1.543</td>
<td>0.137</td>
</tr>
<tr>
<td>Otter Trawl</td>
<td>Crustaceans</td>
<td>19</td>
<td>-0.690</td>
<td>0.499</td>
</tr>
<tr>
<td></td>
<td>Invertebrates</td>
<td>14</td>
<td>-1.326</td>
<td>0.208</td>
</tr>
<tr>
<td></td>
<td>Shrimp Count</td>
<td>2</td>
<td>n/a</td>
<td>n/a</td>
</tr>
<tr>
<td>WTS</td>
<td>Fish</td>
<td>26</td>
<td>-0.846</td>
<td>0.406</td>
</tr>
<tr>
<td></td>
<td>Shrimp</td>
<td>19</td>
<td>1.326</td>
<td>0.201</td>
</tr>
<tr>
<td></td>
<td>Crustaceans</td>
<td>18</td>
<td>-0.846</td>
<td>0.409</td>
</tr>
<tr>
<td></td>
<td>Invertebrates</td>
<td>14</td>
<td>-1.914</td>
<td>0.078</td>
</tr>
<tr>
<td></td>
<td>Shrimp Count</td>
<td>26</td>
<td>-0.846</td>
<td>0.406</td>
</tr>
</tbody>
</table>
During trip two, when the WTS was on the port side and the otter trawl was on the starboard side the WTS again caught significantly less shrimp by weight (n = 24, t = -5.4348, \( p < 0.001 \); Figure 1.8) and fishes (n = 28, t = -6.6692, \( p < 0.001 \); Figure 1.8). The WTS caught 63% less fishes and 35% less shrimp with the WTS was on the port side (Figure 1.7). Additionally, the WTS caught significantly more debris (n = 28, t = 3.1231, \( p < 0.001 \); Figure 1.9) and other invertebrates (n = 28, t = 2.4004, \( p = 0.023 \)) while on the port side (Figure 1.9). The WTS caught 421% more invertebrates and 369% more debris when fished on the port side (Figure 1.7). Also, shrimp count (n=4, t = -0.5704, \( p = 0.608 \)) and crustaceans captured (n=28, t = 1.382, \( p = 0.178 \)) did not differ by gear type. Additionally, catch did not differ between day or night for any of the measured categories when the gear was on the port side (Table 1.2).

![Shrimp Catch with Wing Port Side](image1)

![Fish Catch with Wing Port Side](image2)

**Figure 1.8:** The total Shrimp (left) and fish (right) catch while the Wing Trawling System (WTS) was on the port side and the otter trawl was on the starboard side. Normalized catch is the catch(kg)/(area swept x distance covered). The WTS captured significantly less shrimp (n = 24, t = -5.4348, \( p < 0.001 \)) and fishes (n = 28, t = -6.6692, \( p < 0.001 \)).
Figure 1.9: The total debris (left) and other invertebrate (right) catch while the Wing Trawling System (WTS) was on the port side and the otter trawl was on the starboard side. Normalized catch is the catch/(area swept x distance covered). The WTS captured significantly more debris (n = 28, t = 3.1231, \( p < 0.001 \)) and other invertebrates (n = 28, t = 2.4004, \( p = 0.023 \)).

Size Selectivity

For this portion of the study, 2,672 different fishes were measured to determine if there was any size selectivity between the gear types. The length distribution of \( L. xanthurus \) (D = 0.0693, \( p = 0.702 \)) and \( B. patronus \) (D = 0.0892, \( p = 0.066 \)) did not significantly differ (Figure 1.10). The mean lengths for \( L. xanthurus \) captured by the WTS and otter trawl were 125.23 mm (n=173) and 125.25 mm (n=263), respectively (Figure 1.10). The mean lengths for \( B. patronus \) captured by the WTS and otter trawl were 133.37 mm (n=430) and 131.93 mm (n=428), respectively (Figure 1.9). Additionally, the length distribution of \( L. campechanus \) was found to not significantly differ between gear types (D = 0.1908, \( p = 0.088 \); Figure 1.10). However, it is interesting to note the WTS caught 66 \( L. campechanus \) while the otter trawl captured 127. The mean lengths of \( L. campechanus \) captured were 67.98 mm (n=66) for the WTS and 63.51 mm (n=127) for the otter trawl (Figure 1.10). The WTS caught less \( L. campechanus \) on three out of four tows (Table 1.3). The length distribution of \( M. undulatus \) was found to be significantly larger for the otter trawl (D = 0.1097, \( p = 0.002 \); Figure 1.11). The mean lengths for \( M. undulatus \) were...
undulatus captured by the WTS and otter trawl were 111.38 mm (n=580) and 113.9 mm (n=557), respectively (Figure 1.10). Also, the length distribution of S. maculatus was found to be significantly larger for the otter trawl (D = 0.5382, p = 0.002; Figure 1.11). The mean lengths of S. maculatus captured were 119.81 mm (n=23) for the WTS and 167.36 mm (n=26) for the otter trawl (Figure 1.10). It should also be noted that the otter trawl captured six Red Drum (Sciaenops ocellatus) over 615 mm, and the WTS did not catch any S. ocellatus of that size.

**Figure 1.10:** Average length in mm of S. maculatus, L. campechanus, B. patronus, M. undulatus, and L. xanthurus. Red bars are fish from the WTS and blue bars are from the otter trawl. Error bars are the standard error for each gear type. The lengths of L. xanthurus (D = 0.0693, p = 0.702), B. patronus (D = 0.0892, p = 0.066), and L. campechanus (D = 0.1908, p = 0.088) were not significantly different between gear types. However, the lengths of M. undulatus (D = 0.1097, p = 0.002) and S. maculatus (D = 0.5382, p = 0.002) were significantly larger for the otter trawl.
Table 1.3: Number and location of *L. campechanus* captured with the WTS and otter trawl.

<table>
<thead>
<tr>
<th>Date</th>
<th>Tow #</th>
<th>WTS</th>
<th>Otter</th>
<th>Latitude</th>
<th>Longitude</th>
<th>WTS</th>
<th>Otter</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/5/15</td>
<td>30</td>
<td>n=15</td>
<td>n=28</td>
<td>29°00.259 N</td>
<td>89°07.482 W</td>
<td></td>
<td></td>
<td>29°04.340 N</td>
<td>89°04.179 W</td>
</tr>
<tr>
<td>9/8/15</td>
<td>48</td>
<td>n=2</td>
<td>n=12</td>
<td>29°07.824 N</td>
<td>89°01.319 W</td>
<td></td>
<td></td>
<td>29°05.738 N</td>
<td>89°00.819 W</td>
</tr>
<tr>
<td>9/8/15</td>
<td>49</td>
<td>n=4</td>
<td>n=12</td>
<td>29°05.746 N</td>
<td>89°00.902 W</td>
<td></td>
<td></td>
<td>29°05.192 N</td>
<td>89°01.689 W</td>
</tr>
</tbody>
</table>

Figure 1.11: Visual representation of the Kolmogorov–Smirnov test. On the Y-axis is the cumulative probability that the length lies within the respective distribution. The lengths of *M. undulatus* (D = 0.1097, p = 0.002) and *S. maculatus* (D = 0.5382, p = 0.002) were significantly larger for the otter trawl.

**Multiple Linear Regression on Abiotic parameters**

Multiple linear regressions were performed on the WTS and otter trawl data to determine the effects of surface salinity, turbidity, temperature, DO, and water depth on shrimp and fish catch. Beginning with a saturated model including WTS shrimp catch as the response variable and all of the abiotic variables as fixed effects the model was reduced step-wise. The resulting
model included only DO and conductivity. Both DO ($p = 0.009$) and conductivity ($p = 0.004$) were significant (Table 1.4). DO had the largest coefficient estimate of 0.0982, while conductivity was 0.0115. Similarly, another regression was preformed including all variables as fixed factors, but with otter trawl shrimp catch as the response variable. The final model, after step-wise reduction, only included DO and conductivity (Table 1.5). Both DO ($p = 0.007$) and conductivity ($p = 0.003$) were significant. DO had the largest coefficient estimate of 0.159, while conductivity was 0.0181.

**Table 1.4:** Multiple regression model of WTS shrimp catch as the response variable with surface dissolved oxygen and conductivity as fixed factors. Dissolved oxygen and conductivity were both significant. Dissolved oxygen has the highest coefficient estimate compared to conductivity.

<table>
<thead>
<tr>
<th>Coefficients:</th>
<th>Estimate</th>
<th>Std. Error</th>
<th>t-test</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>0.068539</td>
<td>0.31865</td>
<td>0.215</td>
<td>0.831</td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td>0.098239</td>
<td>0.036203</td>
<td>2.714</td>
<td>0.009*</td>
</tr>
<tr>
<td>Conductivity</td>
<td>0.011467</td>
<td>0.003786</td>
<td>3.028</td>
<td>0.004*</td>
</tr>
</tbody>
</table>

**Table 1.5:** Multiple regression model of the otter trawl's shrimp catch as the response variable with surface dissolved oxygen and conductivity as fixed factors. Dissolved oxygen and conductivity were both significant. Dissolved oxygen has the highest coefficient estimate compared to conductivity.

<table>
<thead>
<tr>
<th>Coefficients:</th>
<th>Estimate</th>
<th>Std. Error</th>
<th>t-test</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>-0.340406</td>
<td>0.488309</td>
<td>-0.697</td>
<td>0.49</td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td>0.158546</td>
<td>0.055478</td>
<td>2.858</td>
<td>0.007*</td>
</tr>
<tr>
<td>Conductivity</td>
<td>0.018162</td>
<td>0.005802</td>
<td>3.13</td>
<td>0.003*</td>
</tr>
</tbody>
</table>

Another set of linear regressions was performed on fish catch for both gear types. Starting with a saturated model including WTS fish catch as the response variable and all of the surface abiotic variables as fixed effects the model was reduced step-wise. The model with the lowest AIC included salinity, conductivity, DO, average depth, and temperature. All of the
variables significantly contributed to the variation in fish catch (Table 1.6). Temperature has the highest coefficient estimate of -0.223, followed by DO with 0.209. Finally, a model as fitted for the otter trawl fish catch using the all of the abiotic variables, treated as fixed factors. The reduced model included salinity, conductivity, DO, average depth, and temperature. Only salinity ($p = 0.029$) and conductivity ($p = 0.003$) were found to be significant (Table 1.7). Like the other models, DO had the largest coefficient estimate with 0.313, followed closely by salinity (-0.167) and conductivity (0.157).

**Table 1.6:** Multiple regression model of WTS fish catch as the response variable with surface salinity, conductivity, dissolved oxygen, average depth, and temperature as fixed factors. All factors resulted in significance. Temperature has the highest coefficient estimate followed by dissolved oxygen.

<table>
<thead>
<tr>
<th>Coefficients:</th>
<th>Estimate</th>
<th>Std. Error</th>
<th>t-test</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>6.6907</td>
<td>2.5375</td>
<td>2.637</td>
<td>0.011*</td>
</tr>
<tr>
<td>Salinity</td>
<td>-0.0710</td>
<td>0.0454</td>
<td>-1.565</td>
<td>0.124</td>
</tr>
<tr>
<td>Conductivity</td>
<td>0.0682</td>
<td>0.0309</td>
<td>2.208</td>
<td>0.032*</td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td>0.2086</td>
<td>0.0757</td>
<td>2.755</td>
<td>0.008*</td>
</tr>
<tr>
<td>Average Depth</td>
<td>-0.0300</td>
<td>0.0097</td>
<td>-3.09</td>
<td>0.003*</td>
</tr>
<tr>
<td>Temperature</td>
<td>-0.2226</td>
<td>0.0934</td>
<td>-2.384</td>
<td>0.003*</td>
</tr>
</tbody>
</table>

**Table 1.7:** Multiple regression model of WTS fish catch as the response variable with surface salinity, conductivity, dissolved oxygen, average depth, and temperature as fixed factors. Salinity and conductivity were both significant. Dissolved oxygen has the highest coefficient followed by salinity.

<table>
<thead>
<tr>
<th>Coefficients:</th>
<th>Estimate</th>
<th>Std. Error</th>
<th>t-test</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Intercept)</td>
<td>0.26833</td>
<td>4.337</td>
<td>0.062</td>
<td>0.952</td>
</tr>
<tr>
<td>Salinity</td>
<td>-0.16723</td>
<td>0.0692</td>
<td>-2.417</td>
<td>0.029*</td>
</tr>
<tr>
<td>Conductivity</td>
<td>0.15734</td>
<td>0.0655</td>
<td>2.402</td>
<td>0.003*</td>
</tr>
<tr>
<td>Dissolved Oxygen</td>
<td>0.31301</td>
<td>0.24908</td>
<td>1.257</td>
<td>0.228</td>
</tr>
<tr>
<td>Average Depth</td>
<td>-0.07664</td>
<td>0.07933</td>
<td>-0.966</td>
<td>0.349</td>
</tr>
<tr>
<td>Temperature</td>
<td>-0.0245</td>
<td>0.14181</td>
<td>-0.173</td>
<td>0.865</td>
</tr>
</tbody>
</table>
Rare species and species of interest
An endangered juvenile Hawksbill Sea Turtle (*Eretmochelys imbricata*) was captured on September 9, 2015 (Figure 1.12). The take occurred between 11:33 AM -1:32 PM in 1.7 m of water. The turtle was captured between 29°07.897, 89°01.297 and 29°07.840, 89°01.104. This turtle was approximately 7.6 cm deep and 30.5 cm long. As required by law, the capture was reported to the NMFS Protected Species Division. Also, an invasive Tiger Prawn (*Penaeus monodon*) was captured on September 2, 2015, between 3:38 PM-5:43 PM. The *P. monodon* was captured between 29°03.835, 89°06.161 and 29°05.112, 89°03.068. The specimen was approximately 23 cm in length (Figure 1.13).

**Figure 1.12:** Juvenile Hawksbill sea turtle captured on 9/9/15 between 11:33 AM -1:32 PM in 5.5 ft of water. Trawl was deployed at 29°07.897 N, 89°01.297 W and picked up at 29°07.840 N, 89°01.104 W. Body depth of the Turtle is approximately 7.6 cm and 30.5 cm long.
Figure 1.13: Photograph of an invasive Tiger Prawn (above) and a large White Shrimp. The Tiger Prawn was collected during the study in the Gulf of Mexico and measured approximately 23 cm.

Discussion

Reduction in finfish bycatch and shrimp catch

The WTS reduced the amount of finfish captured as bycatch, but also reduced the amount of shrimp collected. The observed reduction in shrimp collected would almost assuredly be significant to any fisherman relying on this species for income. Both the otter trawl and the WTS use a tickler chain to elicit an escape response from the shrimp to improve catch efficiency. The tickler chain is set out ahead of the net so that when the shrimp moves off of the substrate the net will be in a position to capture the shrimp. I believe that the WTS is causing the shrimp to react before the tickler chain. This may result in the shrimp jumping over the net. Further compounding this problem could be the size and the species of shrimp that were being collected. The majority of the shrimp that we caught were White Shrimp (*Litopenaeus setiferus*). It has been noted that *L. setiferus* jumps more to evade the net and is more active than the Brown Shrimp (*Farfantepenaeus aztecs*), the other local species fished commercially (Muncy, 1984).
Additionally, both gear were catching relatively large shrimp. The average shrimp count throughout the duration of the study was 58.02 shrimp per kg, which equates to 18 count head on shrimp (eighteen shrimp per pound). These larger shrimp likely travel farther and faster off the bottom than smaller shrimp. Therefore, they are better suited to avoiding the net if they jumped before the tickler chain. The inventor of the WTS, Randy Skinner, believes that using a net with a bib could alleviate the shrimp loss. This would allow the net to be adjusted so that it would open closer to the front of WTS. In theory, with the headrope closer to the front of the trawl, the net will capture more shrimp that reacted to the WTS rather than the tickler chain. In previous fishing trips, outside of this study, a net with a bib had been used with minimal loss of shrimp (Randy Skinner, personal communication). It should also be noted that the overall average weight of shrimp captured on this trip was very low for both gear types. Eleven tows were omitted due to low shrimp catch. The average shrimp catch during this study was approximately 12 kg; this is an economically unsustainable amount of shrimp being captured. Generally, in the shrimping industry if a boat is not catching enough shrimp to at least offset operating cost they will suspend fishing or move to a different area. Due to time constraints, we fished through times where under normal fishing conditions we would have ceased fishing. If more shrimp were captured, as in typical commercial trawling, results may vary considerably, suggesting that further research is necessary to adequately assess the performance of the WTS.

I hypothesized that the reduction in finfish bycatch by the WTS was due to the lack of trawl doors that create mud plumes. These mud plumes act as walls to herd the fish back into the net. Similar to the WTS, skimmer trawls do not use trawl doors and also experience reduced bycatch (Wardle, 1983; Hein and Meier 1995). I also believe that the fishes are being redirected by the presence of the WTS in that the fishes appear to be sensing the wing before they see the
net. It is possible that the fishes then follow the wing from the center out until they are out of the capture zone. Fishes have been observed following the trawl warp and the net down into the belly resulting in capture (Bryan et al., 2014). I believe the fishes are reacting similarly to the WTS and are following the edge of the wing but out of the trawls path. These assumptions are based on the shape of the gear.

The reduction of bycatch and shrimp catch caused by the WTS is similar to that of many other bycatch reduction devices. In a study conducted by Broadhurst (2000), the author found that across thirty-eight different bycatch reduction devices the average shrimp loss was 29% and the average bycatch reduction was 60%. This matches very closely to the WTS bycatch reduction and shrimp loss. It should be noted that the previous studies took place in many different environments capturing different species. Different species of bycatch and shrimp will react differently to a trawl. There is no single bycatch reduction device that will work well with all environments and species.

*Increase in debris and invertebrate catch*

The WTS caught more debris and invertebrates than the otter trawl throughout this study. This suggests that the WTS is fishing closer to the benthos than the otter trawl. On the nineteenth tow, the captain added weights in equal proportions to the footrope of each net. The weights caused the WTS to fish closer to the ground when compared to the otter trawl. The weights were added because the captain was concerned that the nets were not fishing completely on the seafloor.

A paired t-test ($\alpha = 0.05$) was run to assess the affect of the weight addition. Comparing the first eighteen tows without the weights and the next eighteen tows with the weights I found
the WTS catch was affected by the addition of weights (Table 1.8). The catch of the WTS was not significantly different for fish and crustaceans (Table 1.8). The catch was significantly different for shrimp \((n = 18, t = 2.765, p = 0.013)\), invertebrates \((n = 17, t = -3.521, p = 0.003)\), and debris \((n = 17, t = -3.438, p = 0.003;\) Table 1.8). The otter trawl catch was not significantly different for fish, crustaceans, invertebrates, and debris (Table 1.8). The catch difference was significant for shrimp \((n = 18, t = 3.814, p < 0.001)\). Due to the significant differences between invertebrate and debris comparisons before and after the weight additional my results for those two categories could be affected. Additionally, while the shrimp differences were significantly different, they were significant for both the WTS and the otter trawl. This suggests that the difference in shrimp catch is caused by variations in time and space rather than the addition of the weights.

**Table 1.8:** Results of the t-test's assessing the affect of the addition of weight to the headrope. The test compared the catch before and after the addition of the weight. The addition of weight significantly affected shrimp catch for the otter trawl. The addition of weight significantly affected shrimp, crustacean, and debris catch for the WTS.

<table>
<thead>
<tr>
<th>Gear Type</th>
<th>Categories</th>
<th>n</th>
<th>t</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Otter Trawl</td>
<td>Fish</td>
<td>17</td>
<td>-0.718</td>
<td>0.483</td>
</tr>
<tr>
<td></td>
<td>Shrimp</td>
<td>18</td>
<td>3.814</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Crustaceans</td>
<td>14</td>
<td>0.734</td>
<td>0.476</td>
</tr>
<tr>
<td></td>
<td>Invertebrates</td>
<td>17</td>
<td>0.115</td>
<td>0.910</td>
</tr>
<tr>
<td></td>
<td>Debris</td>
<td>17</td>
<td>-1.080</td>
<td>0.296</td>
</tr>
<tr>
<td>WTS</td>
<td>Fish</td>
<td>17</td>
<td>-1.373</td>
<td>0.189</td>
</tr>
<tr>
<td></td>
<td>Shrimp</td>
<td>18</td>
<td>2.765</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td>Crustaceans</td>
<td>14</td>
<td>1.918</td>
<td>0.077</td>
</tr>
<tr>
<td></td>
<td>Invertebrates</td>
<td>17</td>
<td>-3.521</td>
<td>0.003</td>
</tr>
<tr>
<td></td>
<td>Debris</td>
<td>17</td>
<td>-3.438</td>
<td>0.003</td>
</tr>
</tbody>
</table>
I hypothesized that the addition of weights can cause the headrope height to decrease and subsequently increase the capture of debris and invertebrates on the seafloor. When comparing a semi-pelagic trawl to an otter trawl, there is a large decrease in the amount benthic fish and invertebrates captured due to a 25 cm increase in footrope height (Ram et al., 1993). Similarly, raising the footrope height on an otter trawl was found to reduce the number of benthic species captured (Weinberg et al., 2002). The chance of capturing a benthic oriented organism has been correlated to the headrope height in otter trawls. Weinberg et al. (2004) determined that increasing headrope height could exclude smaller species of Red King Crab (*Paralithodes camtschaticus*), going as far to establish a linear correlation to size of crab and likelihood of capture, ranging from 20-80% based on the size of the crab. Depending on the size of the organism, a headrope height of 1 cm could result in a capture rate of 100% (Weinberg et al., 2004). It is possible that the WTS could have been affected more by the addition of weights because the net is not being stretched like the otter trawl; it is attached to fixed points. The otter trawl has a constant outward pulling force from the doors, possibly reducing the effects of the added weight and keeping the headrope height higher than the WTS.

*Day and night testing*

I hypothesized that there would be a difference between day and night catches with the WTS. If the WTS is reducing finfish bycatch by providing a visual cue before the net, then I would expect the highest reduction in bycatch or shrimp during the day. Similarly, I would expect to catch more shrimp or finfish bycatch during the night if I thought the WTS was causing them to react early during the day. However, I found that there were no significant differences between day and night catches. Either gear type provides both a visual cue and an audible cue.
The otter trawl disturbs the sediment with the boards producing a visual cue. Dragging the boards along the ground creates an audible cue. The WTS is a visual cue before the net and it will make noise as it is dragged along the benthos as well. Engås and Godø (1986) found no differences between day and night catches using an otter trawl. They found that while they may not be able to see the trawl as well at night they were still able to hear the trawl and react to it, noting that fish herded similarly during the day and night (Engås and Godø, 1986). It is also possible that finfish responses to the amount of light present are more species dependent (Casey and Myers 2011). Throughout this experiment I captured 51 different species of finfish and in my analysis I did not separate the catch into individual species, possibly obscuring any specific finfish responses due to species differences (Appendix 1). Much of the literature refers to sight as the largest factor in capture. Sound alone is not enough to elicit an escape response in time; a visual cue must also be provided for an organism to escape in time (Glass and Wardle 1989; Walsh and Hickey 1993). Glass and Wardle (1989) noted that in very low light conditions fish only reacted to the trawl when they come in contact with it. The ability of an organism to escape a trawl depends on the amount of time it has to react to the trawl. In clear water with high light the organism will have more time to react to the trawl and a greater chance of escaping (Petrakis et al., 2001).

In an attempt to video the fish behavior in response to both gear types, I came across a potential answer as to why WTS and otter trawl capture success was not affected by the amount of light present. While this was only attempted once, it was clear that I would be unable to video the behavior of the fishes during the day or night because the water clarity was markedly poor near the trawl due to ambient water conditions. For this reason, it is likely that the fishes and shrimp were not reacting to the WTS as a visual cue because they may not have seen it during
the day or night time. Instead, it is likely that the WTS may be providing a proximal cue before the trawl, allowing enough time for the finfish and shrimp to escape the net.

Size differences in selected species

I found that the WTS caught significantly smaller *M. undulatus* and *S. maculatus*. Larger fishes may be more able to avoid the WTS. This is especially clear with the differences seen in the *S. maculatus* lengths. There was a 57 mm difference between the two gear types for the average of *S. maculatus* measured (Figure 1.10). *S. maculatus* have highly developed eyes (Tamura and Wisby, 1963), and these fish may be able to react to the WTS in time to avoid it. Also, *S. maculatus* are capable of high swimming speeds. A similar species Atlantic Mackerel (*Scomber scombrus*) can sustain speeds of 5 m/s for a short amount of time (Wardle, 1988). The average net speed for this study was 1.3 m/s, slow enough for *S. scombrus* to avoid the net. Additionally, the WTS did not catch any large *S. ocellatus*. The exclusion of larger *S. ocellatus* is likely due to the size and speed capabilities (Bainbridge, 1958), and well-developed eyesight (Fuiman and Delbos, 1998) of this species. Finally, the WTS caught almost half as many *L. campechanus*. I subjectively attribute this reduction due to the lack of trawl doors, creating mud plumes that heard the fish and the presence of the WTS providing a proximal cue before the trawl.

Multiple Linear Regression on Abiotic parameters

DO was the largest contributor in three out of the four models on shrimp and fish catch for the otter trawl and WTS. For both models including shrimp catch as the response variable for both trawls, DO and conductivity had a significant positive correlation. DO was the largest
contributor to the variation in shrimp catch. Shrimp are benthic species and would be particularly effected by low oxygen level because they are not as mobile as many fish. Renaud (1986) conducted a trawl survey and found that shrimp catch never exceeded 2 kg when the water was hypoxic. He noted that both *F. aztecs* and *P. setiferus* both avoided water with DO of less than 2 mg/l (Renaud, 1986). During my study, we captured less than 2 kg of shrimp on five tows when the DO was less than 4.3 mg/l. While our DO measurements were not hypoxic, it has been shown that a similar species, *F. aztecus*, shows a preference for higher oxygen water. In a laboratory experiment *F. aztecus* spent 65% more time in water with 6 mg/l of DO compared to 4 mg/l (Wanamaker and Rice, 2000). Another study conducted on a related species, the Greasyback Shrimp (*Metapenaeus ensis*) concurs that penaeid shrimp are able to detect low oxygen areas and avoid them (Wu, 2002). It should be noted that pinpointing the exact affects of low oxygen on shrimp is difficult in nature because they tend to avoid low oxygen areas and they are able to move out of them (Craig and Crowder, 2005). Salinity and conductivity are very similar measurements and often appear collinear in abiotic data sets. It is unclear why conductivity would be a significant factor in these models while salinity is not.

Similar to the models with shrimp catch as the response variable, fish catch was also heavily influenced by DO. The final models with fish catch, though, were not as reduced as the shrimp catch models. I attribute this to the number of species that were included under the same analysis. The models with shrimp and the response variable only included two species of shrimp, whereas, the fish model contained at least fifty different species. Different species of fishes tolerate different levels of DO and exhibit different behaviors to low oxygen environments (Breitburg, 1992; Breitburg et al., 2001). Additionally, it could be assumed that salinity, conductivity, average depth, and temperature would also have different effects on different
species. However, it is generally agreed that fish avoid areas of low oxygen or they will leave areas that have reduced oxygen levels (Renaud, 1986; Howell and Simpson, 1994; Eby et al., 2005). The level at which fish are effected by decreased DO is often disputed. The commonly accepted DO concentration for hypoxic water is < 2 mg/l. Vaquer-Sunyer (2008) argues that this number is not appropriate, citing metadata on 872 papers on hypoxia they found that 10% of the fish population would be affected at DO levels below 4.6 mg/l. An earlier study noted a significant decrease is species richness in DO levels below 3 mg/l (Howell and Simpson, 1994). During this study the surface water measurements never reached a hypoxic level, but it is likely that the bottom water measurements were lower. The models with fish catch are not as clear, the only trend that is consistent across both gear types is DO. In the model with WTS fish catch, conductivity is significant, but salinity is not. Additionally, salinity has a negative relationship with fish catch, while the relationship with conductivity is positive. Again, I think this could be attributed to the large number of fish species used in this one analysis. This portion of the analysis would have benefited from more abiotic readings and bottom water measurements. However, due to time and gear constraints this was not possible.

**Sea turtle capture**

The hawksbill sea turtle (*E. imbricate*) is currently listed on the IUCN red list as critically engendered (IUCN, 2008). The decline of *E. imbricate* is likely due to the appearance of its shell and not because of its use as a food source. The shells are commonly used to make jewelry, due to their ‘tortoise shell’ pattern (Witzell, 1983). From 1923-1975, a sea turtle fishery harvested an average of over 1000 kg of *E. imbricate* per year (Witzell, 1994). The capture of the *E. imbricate* during this research was a rare occurrence, due to where it was collected. It was
captured close to the southeastern edge of the Louisiana delta in 1.7 m of water. Data from turtle strandings from 1980-1994 on the Texas and Louisiana coasts found that of 3,283 strandings only 1.7% were *E. imbricate* (Cannon, 1998). Additionally, only 0.7% of those strandings were found near inshore waters (Cannon, 1998). The majority of the *E. imbricate* population and nests are found in the Caribbean and as of 2006, there were approximately less than 30,000 individuals in existence (McClenachan, 2006). Some species of sea turtles, such as green turtles (*Chelonia mydas*), exhibit natal a homing response, where they return to nest on the same beaches on which they were hatched (Allard et al., 1994). It was hypothesized that *E. imbricate* followed a similar behavior. One study conducted in the Caribbean found that 58-78% of *E. imbricate* exhibit natal homing (Velez-Zuazo et al., 2008). Another tracking study conducted by van Dam et al. (1998) found that turtles did not travel farther than 2 km from their natal nesting site. Furthermore, other studies found that *E. imbricate* was highly migratory (Bass et al., 1996; Whiting and Koch, 2006).

While the migratory patterns of *E. imbricate* may not be clear, it is generally accepted that as sea turtles mature from juveniles to sub adults they move from the pelagic zone to the neritic zone (Bolton, 2003). At a straight carapace length of 20-35 cm *E. imbricate* migrates from the pelagic zone closer to shore for better foraging grounds (Musick et al., 1997; Bolton 2003). The turtle that we captured was within the predicted size for turtles to be transitioning from their pelagic life stage (23 cm; Figure 1.12). While many *E. imbricate* return to the same nesting habitat, some forage hundreds to thousands of miles away from the natal homes (Bowen et al., 2007). Bowen *et al.* (2007) linked 43 strandings of *E. imbricate* in Texas from Caribbean stocks. He suggested that they could have been trapped in the Gulf of Mexico due to prevailing ocean currents. It is possible that the turtle I encountered suffered the same fate.
**Tiger prawn capture**

Tiger Prawns (*P. monodon*) are becoming a more frequent catch in Louisiana. The first report in Louisiana of the Tiger Prawn came in 2007. This number went up to almost 130 reports in 2011 to 9 individuals reported in 2012 (Fuller, 2014). The individual I captured (23 cm) was a mature adult. The invasion of *P. monodon* likely came from established populations in the Caribbean or from aquaculture facilities on the Atlantic (Fuller, 2014). There is concern that this shrimp will compete with native species because of its large size and generalist diet (Fuller, 2014). It is interesting that a majority of the takes occurred in Louisiana waters. This may be because of the higher amount of commercial shrimping effort in the area causing an inflation of reports. In another survey by USGS, Tiger Prawn distribution remained similar between the western gulf coast states (AL, LA, MS; Figure 1.14)

![Map of Tiger Prawn reports in the western Gulf States](image)

**Figure 1.14:** Amount and distribution of Tiger Prawn reports in the western Gulf States (AL, LA, MS). Darker larger circles represent more reports of the invasive shrimp. The red square is the locality where a Tiger Prawn was collected during the current study.
Side bias

When a boat catches more on one side of the boat it is known as side bias. Data analysis was separated by trip due to the phenomena of side bias. During this experiment, I measured a large difference in catch between the first and second trips when the gear was on different sides of the vessel. This can be attributed many different factors such as: the captain may unintentionally favor turning the boat to one side, the boat may have a slight lean to one side or the other, or the nets could be slightly different. Favoring turning the boat to one side will cause the outer trawl to cover a larger area. The effect of turning was limited by making an equal amount of turns. Therefore, the catch was not likely to have been influenced by the direction the boat was turning. The large differences in catch may have been seen due to spatial and temporal differences in the fishing effort as well. The vessel was not always fishing the same waters and the shrimp were not always present in large numbers. Price and Gearhart (2011) switched the control and experimental nets every day to account for this. This method could not be applied because of the difficulty of moving the WTS from one side to the other. I believe that spatial and temporal differences between the first and second trip when the trawls were fished on different sides account for the large difference seen in catch.

Conclusions

In conclusion, based on the results of this research, the WTS is an effective trawl to reduce bycatch. With an average bycatch reduction of over 60% when compared to an otter trawl, it is clear the WTS will reduce the number of fish captured. However, the WTS did not retain nearly as many shrimp as the otter trawl. A reduction of shrimp catch of over 30% may end up being too large of a number for Gulf fisherman to embrace this new gear type. Using a net with a bib
may alleviate shrimp loss. Additional studies need to be conducted to determine the benefits of using such a net. The ability of the WTS to exclude large fish is an interesting side effect that could help reduce the damage shrimp trawls can cause to fish populations.

Work Cited


Main, Jody, & Sangster, GI. (1981). *A study of the sand clouds produced by trawl boards and their possible effect on fish capture.*


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**Chapter Two**
Benthic Disturbance by the Wing Trawling System (WTS) in Comparison to an Otter Trawl

Introduction

Disturbances in benthic habitats from bottom trawling have been compared to the ecological devastation of clear cutting forests, threatening the biodiversity and economic viability of the ecosystem (Watling and Norse, 1998). Relatively speaking, the seafloor may seem like an insignificant part of the ocean’s ecosystem, but the organisms that occur there help stabilize sediment, reduce turbidity, and process excess nutrients (Thrush and Dayton, 2002). The effect of bottom trawling is not as simple as the clear cutting of a forest; the true effect will depend on many factors such as the organisms present, their resilience to disturbance, the fishing effort in the area, and the type of habitat (Collie et al., 2000; Kaiser et al, 2003; Pitcher et al., 2009). Fishing effort can be highly variable, ranging from grounds being fished three times a day, to places where only 20% of fishable areas are exploited per year (Thrush and Dayton, 2002). For example, areas with higher fishing pressure will likely experience more adverse effects from trawling, while areas of lower fishing pressure will have little to no effects; community structure of benthic organisms will likely differ as well, based on the frequency of disturbance.

Studies addressing the impact of trawls on community structure in benthic habitats have resulted in variable conclusions. Conclusions ranged from insignificant changes to the ecosystem (Kaiser et al., 1999; Drabsch et al., 2001; Burridge et al., 2006) to a removal of 90% of the organisms in a single tow (Sainsbury et al., 1993). Burridge et al. (2006) found no differences between an area open to trawling and an area that has been closed to trawling. He reasoned that the lack of difference seen in the benthic communities could be due to habitat
complexities across the sampling areas. Drabsch et al. (2001) completed a Before-After, Control-Impact (BACI) experiment using an un-trawled area as the control and found no differences in the benthic communities. He cited differences in benthic community structure and spatial and temporal differences in sampling as the reason for the similarities between trawled and untrawled areas. Additionally, similarities between trawled and untrawled areas could be due to the ability of some benthic organisms to re-populate disturbed areas quickly (Kaiser et al., 1999). Results of previous studies were variable due to a number of factors such as a lack of a true control and insufficient repetition of studies (Engel and Kvitek, 1998). At the time when many of these experiments were completed, limitations in GPS technology resulted in imprecise simulations of trawling pressure (Burridge et al., 2003). Additionally Bradshaw et al. (2012) noted that bottom trawling could resuspend harmful pollutants from the seafloor. In general, most studies conclude that while the effects of trawling are difficult to quantify, the results are a shift from long-lived, large, sessile invertebrates to small, soft-bodied, opportunistic species (Thrush et al., 1998; Tillin et al., 2006; de Juan et al., 2007; Olsgard et al., 2008; Svane et al., 2009; van Denderen et al., 2013). It should be noted that the affect of bottom trawling on a benthic ecosystem is a function of organisms’ vulnerabilities and the speed at which they can recollinze the area (Pitcher et al., 2000). Although few remedies exist to alleviate the bottom disturbance associated with trawling, one solution would be to raise the trawl off the bottom; however, raising the trawl will reduce the chances of capturing benthic species such as shrimp (Moran and Stephenson, 2000). Other solutions include reducing the depth of the trawl penetration into substrate by constructing lighter trawls and reducing the surface area of the trawl that comes in contact with the seafloor (Valdemarsen et al., 2003).
My current study assesses the issue of minimizing benthic habitat disturbance by reducing the area of the trawl that comes in contact with the seafloor. Randy Skinner, an Alabama shrimper and inventor of the Wing Trawling System (WTS; Figure 1.1), claims to have invented an alternative to an otter trawl that will reduce the disturbance bottom trawls have on the benthos. Unlike otter trawl doors that create clouds of displaced sediment the length of a trawl door (Main and Sangster, 1981; Wardle, 1986), the WTS only has three shoes totaling less than 1 m of bottom contact. By reducing the footprint of the WTS, the idea is to alleviate the more extreme benthic scouring caused by the trawl doors. The trawl net associated with the WTS essentially functions the same as that associated with traditional wooden or aluminum otter trawl doors. For both gear types, the net fully opens and the ground rope skims along the water bottom. A tickler chain is located forward of the ground rope. This agitates the sediment ahead of the net, forcing shrimp from the benthos where they are then more easily captured by the trawl.

To determine if the WTS is less destructive to substrate habitat versus typical otter trawling, my research objectives were to:

1. Compare the size and depth of the scars left behind by the WTS and otter trawl and

2. Assess the turbidity of the water behind the wing trawl compared to the otter trawl.

**Materials and Methods**

The M/V Apache Rose, a 19.8 m steel shrimp trawler with a 6.7 m beam powered by two 350 hp engines, pulled the WTS and otter trawl simultaneously in a paired test design. The WTS
was comprised of an 11.582 m wing trawl with a 13.716 m two-seam net. The otter trawl was comprised of an identical two-seam net, but with 2.438 x 1.016 m wooden doors (Figure 1.4).

Trawls leave behind marks or scars by displacing sediment. Larger, heavier trawls will leave larger scars and disturb more benthic habitat (Brylinsky et al., 1994). Previous studies have used side scan sonar, photography, and physical measurements to characterize the presence and size of these scars (Brylinsky et al., 1994; John Steele et al., 2002; Løkkeborg, 2005). I used the National Marine Fisheries Service (NMFS) divers to give an in-situ measurement of the trawl scars (Workman, 1986). This portion of the study took place in Panama City, Florida, during the second week of June 2015. Tows were conducted off the coast of Panama City where the water is generally clearer than the water found around Louisiana and the benthos consists of a more sandy bottom than the generally mud/clay water bottoms off Louisiana. This enabled the divers to see the performance of each trawl underway and to physically measure the scars left behind by the trawls in the substrate. After the divers measured the dimensions of the nets they dropped off the net to find and measure the scars left behind by the otter trawl doors and WTS shoes. Due to excessive wave height and prevailing conditions, the water clarity was low and the divers were unable to find the trawl scars left behind by either trawl. Clearer water and calmer seas were needed for this portion of the study to be successful.

Throughout the course of the study I planned to capture the sediment plumes produced by the WTS and otter trawl by photography. The plumes were recorded on a GoPro© mounted on the highest point of the boat (~50 ft.) pointed at the stern (at an angle of ~85°). The time-lapse function was used, capturing many photographs of the plumes over a variety of conditions and substrates. Many hundreds of photographs were taken, but none of them were able to capture the entire plum of the WTS or the otter trawl. The sediment plumes were too far away for the
GoPro’s® wide field of view to capture. A camera with a greater zoom or narrower field of view was required.

Due to the previous unsuccessful attempts at quantifying the sediment disturbance created by the WTS, I returned to the field on December 12, 2015 in Bon Secour Bay, AL. The goals were to measure the depth of the trawl scars made by both trawls and to identify the amount of sediment disturbed off of the bottom. A grid of buoys approximately 120 m wide by 300 m long was set up as the study area (Figure 2.1). A control cast was made with a Conductivity, Temperature, and Density (CTD) meter (Sea Bird Electronics) in the middle of the first set of buoys. Additionally, three grab samples were taken using a ponar dredge to characterize the type of sediment I was trawling over. I then used a River Ray Acoustic Doppler Current Profiler (ADCP; Teledyne RD Instruments) to make transects heading south then north along each set of buoys. The ADCP has four sonar beams with a frequency of 600 kHz to measure depth. Once all control measurements were taken, the F/V Apache Rose trawled through the grid with both the WTS and Otter trawl. When the vessel passed through the first set of buoys I began making CTD casts about 100 m behind the outriggers of the fishing vessel. Sediment plumes were easily visible from the otter trawl; therefore, casts were made on the outside of the otter trawl so that propeller wash did not influence the turbidity readings. Sediment plumes created by the WTS were not readily visible from the surface; therefore, casts were made on the inside on the WTS as to not miss the trawl entirely. Three successful CTD casts were made behind both the WTS and otter trawl. After the fishing vessel passed through the grid, replicate ADCP transects were made across each set of buoys. Two transects were made going both north and south. To capture the depth of penetration by the WTS and the otter trawl, the boat had to be moving very slowly. We estimated that the width of each shoe of the
WTS was around 0.3 m and with the ADCP sending a sonar signal once every second it would be difficult to capture (Figure 2.2). The methods I used were modified from those of Bradshaw et al. (2012) and Madron et al. (2005).

**Figure 2.1:** Grid used to assess the depth of trawl scars and turbidity of the water behind the otter trawl (left) and WTS (right). As the F/V Apache Rose passed through the grid, 6 CTD casts were made behind each trawl. Once the fishing vessel passed through the grid, ADCP transects were made to determine the depth of trawl scars. Two transects were made at each buoy, with and against the current.
Figure 2.2: Schematic of the fishing vessels trawls. The otter trawl will displace between 3.4 and 4.2 m of sediment on the seafloor, while the WTS will only displace .9 m.

Statistical Analysis

We planned to visually compare the depth of the trawl scars, but due to the difficulties caused by the waves this was not possible. Therefore, we averaged the sonar feedback from the four beams and compiled the transects into control and experimental for each buoy. We then compared the variance of the control and experimental depths using an f-test (α = 0.05). My null hypothesis was that the variance would not differ between the control and experimental transects.

Due to possible influences of propeller wash, only water depths of 0.45-2.1 m were analyzed. For depths less than 2 m to the max depth of 2.82 m, the turbidity was uncharacteristically high suggesting that the sediment disturbance was influenced more by the propeller wash then the trawl. As noted earlier the mud plumes from the WTS were not visible from the surface, meaning that any increase in turbidity in the middle to top of the water column
was due to the effects of the WTS and not the propeller wash. This could also occur on the otter trawl side then the boat is turning, causing the trawl to come closer to the propeller wash. The ambient water turbidity was subtracted from the measurements to ensure that the readings correlated to only sediment disturbance caused by the trawls. The differences of turbidity were tested with a paired t-test \((\alpha = 0.05)\). My null hypothesis was that there is no difference between the amounts of disturbance caused by either trawl type.

**Results**

Out of the four experiments I attempted to identify the amount of disturbance the WTS causes, only two of them were successful. Both the NMFS divers and the GoPro© were unsuccessful at quantifying the benthic disturbance due to weather and technology limitations. However, the ADCP and CTD casts made yielded useful, interpretable results. The ADCP readings were limited by the variation caused by the waves, therefore only a range on the possible trawl scar depths can be given (Figure 2.3). While the ADCP transects were difficult to visually compare, all three control and experimental transects at each buoy had significantly different variances (Buoy 1: \(F = 0.6489, p < 0.001\); Buoy 2: \(F = 0.4153, p < 0.001\); Buoy 3: \(F = 0.6626, p < 0.001\); Tabel 2.1). The variance and standard deviation of the control transects made before the trawl came through were very low (Table 2.1). This suggests that the seafloor topography is mostly flat. To figure out the possible depth of the trawl scars, I evaluated the difference of the maximum depth value between the control and experimental transects. This generated a range of 9.9-13.6 cm (Table 2.1). It was unclear how deep the trawl scars were for either trawl, but based on our estimates of the scars created by both trawls it is certain that the depth of the WTS scar is equal to or less than the otter trawl.
Figure 2.3: ADCP transects produced by WinRiver II. The graph (a) was the control depth profile before the gear was trawled through. Graph (b) and (c) are the experimental transects after the trawl came through. Transect (b) was taken from north to south. Transects (a) and (c) were taken from south to north. I could not differentiate between the two gears trawls scars due to the low resolution of the data.
Table 2.1: Variance, standard deviation, max depth, and the difference of max depth between the control and experimental transects. These values are compiled from 2 transects for each control and 4 for each experimental run across the three sets of buoys. All three control and experimental transects at each buoy had significantly different variances (Buoy 1: $F = 0.6489, p < 0.001$; Buoy 2: $F = 0.4153, p < 0.001$; Buoy 3: $F = 0.6626, p < 0.001$).

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<th>Buoys</th>
<th>Control</th>
<th>Experimental</th>
<th>Variance</th>
<th>SD</th>
<th>Max Depth (m)</th>
<th>Depth Difference (m)</th>
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<td>0.03579</td>
<td>0.04396</td>
<td>2.9275</td>
<td>0.1361</td>
</tr>
</tbody>
</table>

Analyzing the middle 0.45-2.1 m of water I found that the WTS disturbed significantly less sediment then the otter trawl ($t = 4.9477, n = 34, p < 0.001$). The ambient water conditions were on average 4.04 NTU (Figure 2.4). The turbidity of the WTS less the ambient water turbidity was 18.6 NTU, while the turbidity behind the otter trawl was 206.8 NTU (Figure 2.4). The WTS produced over a 90% reduction in turbidity.

Figure 2.4: Comparison of the turbidity of the WTS, otter trawl, and the ambient water conditions. Casts were made with a CTD. Analyzing the middle 0.45-2.1 m of water we found that the WTS disturbed significantly less sediment then the otter trawl ($t = 4.9477, n = 34, p < 0.001$). Error bars are standard error.
Discussion
Benthic Disturbance

It is clear through our testing that the WTS disturbs less sediment and creates a trawl scar that is equal to or less that the scar created by an otter trawl. I believe that the WTS disturbs less sediment because less of the trawl comes in contact with the ground. The WTS has three shoes 0.3 m wide each, covering a surface area of less than a meter (Figure 2.2). The otter trawl doors cover a much larger area; depending on the angle the doors are towed at (35-45°) the otter trawl doors will disturb 3.4-4.2 m of sediment (Figure 2.2). Additionally, it was evident through the videos taken by the NMFS divers that only the heels of the WTS come in contact with the seafloor (Figure 2.5). In comparison the entire edge of the otter trawl door is contacting the benthos (Figure 2.5). Another factor that could influence the level of sediment disturbance and the depth of the trawl scars is the weight of the trawl doors. An otter trawl door of dimensions 1.0 x 2.5 m weighs between 80-150 kg, while the entire WTS weighs around 550 kg. While the WTS is much heavier than the otter trawl, the scar left behind was equal to or less then that of a typical otter trawl, a factor likely due to hydrodynamic differences between the two gears. The footprint of the WTS is around 75% less than the otter trawl, and it suspended 90% less sediment. The decrease in sediment suspension is disproportionate to the decrease in the trawl footprint, suggesting that the WTS leaves a shallower trawl scar.
Figure 2.5: Photographs of the Otter trawl (a) and WTS (b) and (c). The pictures offer a possible explanation as to why the WTS disturbs the benthos much less. It appears that the WTS only contacts the seafloor with the heel of the trawl while the otter trawl contacts the floor along the length of the board, disturbing large amounts of sediment. The photographs were taken from videos provided by NMFS divers.

**ADCP error**

The sonar data from the ADCP was difficult to interpret because there was disturbance from waves colliding with the boat. The waves were 0.3-0.5 m but they were large enough to disturb the quality of data produced. The wave action was also irregular; making it difficult to fit a filter to the data series to draw out the troughs where the trawl scars would occur. The end result of 9.9-13.6 cm trawl scars agrees with previous studies, which found that otter trawls leave
trawl scars between 5-10 cm (Krost, 1989; DeAlteris, 1999; Hall- Spencer, 2002; Ivanović, 2011). However, a study conducted by Dellapenna (2006) reported measuring a trawl scar from an otter trawl to be 1.5 cm. They estimated the depth with results from side scan sonar and changes from pre and post trawl redox potential discontinuity (Dellapenna, 2006). The construction, size, how the board is fished, and sediment composition can affect the depth that a trawl door. Not all trawl doors are constructed the same. They can be made of metal or wood, including different proportions of metal bracing that will affect its weight. Additionally, larger trawl doors are likely to leave larger scars; the trawl doors used in this study measured 2.438 x 1.016 m. The trawl doors in the study by Dellapenna (2006) were estimated in size to be 1.5 x 2.5 m, but they could have been lighter than the doors we used. How the captain fishes the boards can also affect the penetration. For example, if too little wire is let out for the boards they will fish on the heel, which may lead to a shallower trawl scar. Sediment composition can also affect the depth at which the trawl will penetrate the seafloor. In sandy mud, Ivanović (2011) found that an otter trawl penetrated the sediment 6-8 cm, but on a sandy substrate the trawl penetrated 3-4 cm. The grab samples that I collected indicated that the sediment on the seafloor was very soft, mostly clay in composition. In this softer sediment I would expect the trawls to penetrate the seafloor deeper. With deeper penetration in softer sediments such as clay, benthic communities are more affected in comparison to harder sediments such as sand (Hiddink et al., 2006).

**CTD error**

As with all scientific research, there was some human error associated with using the CTD to measure the turbidity of the trawl scars. Using a second boat to follow the shrimp vessel
was the best way to gather *in situ* data on the sediment plumes created by the trawls using the resources we had. It was often difficult to align the chase boat behind the trawl and then to cast the CTD in the desired location. Also, as mentioned earlier, the WTS did not produce a sediment plume visible from the water surface, so I was forced to cast the CTD on the behind the WTS, but more towards the middle of the boat where it was likely to be influenced by propeller wash. This was not an issue on the otter trawl side, because the sediment disturbance caused by the door was evident on the water surface. Therefore we cast the CTD behind the outside board. This was also difficult because the sediment plume on the outside was less then 3 m wide. It was evident in the data that sometimes the CTD casts were made out of the influence of trawl door, for the analysis these were excluded. Bradshaw et al. (2012) used an additional pair of CTDs suspended 2 m above the seafloor. The use of additional stationary CTDs could help reduce the amount of human error experienced with attempting to make casts behind the trawls.

**Conclusions**

When assessing the successful survey methods I employed, I found that the WTS disturbed 90% less sediment than the otter trawl. Additionally, the trawl scars left behind by the WTS were the same depth or likely shallower compared to the otter trawl. The combination of these two metrics suggests that the WTS would be a viable option to reduce the impact that bottom trawling causes on the seafloor.

**Work Cited**


Appendix 1:
Fish Species encountered

<table>
<thead>
<tr>
<th>Fish Species</th>
<th>Scientific Name</th>
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<td>Southern Stargazer (Astroscopus y-graecum)</td>
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<td>Florida Pompano (Trachinotus carolinus)</td>
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</table>
Vita

The author was born in Baltimore, Md. He obtained his Bachelor’s degree in marine biology from the University of Delaware in 2010. He joined the University of New Orleans Earth and Environmental Science graduate program to pursue a MS under Dr. O’Connell in 2014.