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An Evaluation of a Reduced bar Spacing Turtle Excluder Device in the U.S. Gulf of Mexico Offshore Shrimp Trawl Fishery

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Michel Anthony Nalovic

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This thesis is submitted in partial fulfillment of
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ABSTRACT

Shrimp are the most economically valuable internationally-traded seafood commodity, and wild-caught, trawled shrimp make up almost half of the ~6.6 million metric tons of annual global production. Shrimp trawling is responsible for one-third of the world's total fisheries bycatch, leading many to consider shrimp trawling to be the single most destructive fishing practice in the world. Though the bycatch of large marine animals can be significantly reduced by use of turtle excluder devices (TEDs) on shrimp trawls, current TED designs are ineffective at reducing the capture of smaller organisms which represent a large portion of the total bycatch. To further reduce bycatch in the United States Gulf of Mexico shrimp trawl fleet, a variety of bycatch reduction devices (BRDs) are currently being used in conjunction with TEDs. I evaluated the efficiency of a new TED design, intended to reduce bycatch and maintain target shrimp catch. The new TED model is characterized by 5-cm spacing between flat bars, as opposed to the current industry standard of 10-cm spacing between round bars. Comparative towing experiments under standard commercial shrimp trawling operations in waters off of Georgia, Texas and Mississippi during the summer of 2012 demonstrated shrimp losses or gains of -4.32%, +6.07%, -1.58% respectively and an overall reduction in the capture weight of sharks (41.1-99.9%), rays and skates (76.5-93.4%) and horseshoe crabs (100%). These experiments were limited in time and space, and therefore not fully representative of fishing conditions throughout the year, but this study demonstrates the new TED's effect on the catch rates of target shrimp and bycatch. This thesis research should lead to a broader understanding of the benefits of using reduced spacing flat bar TEDs in the U.S. shrimp trawl industry.

CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW

The modern otter trawl was first used in England or Ireland around 1860 to capture groundfish (Kennelly et al. 2002). Shrimp trawls (STs), a form of otter trawl, were first developed on the southeast coast of the United States near St. Augustine, Florida in 1906 by Solicito "Mike" Salvador, an Italian immigrant (FAO 2008). Prior to the introduction of otter trawls, the U.S. shrimp fishery was seasonal and near shore, and the fishing techniques were limited to the use of haul seines, cast nets, dip nets and baited traps (Rathbun 1882; Hoar et al. 1992). Over the next three decades there were several developments to STs and the technology spread throughout the United States and adjacent waters including Mexico and South America (Iverson et al. 1993; FAO 2008). The use of STs later migrated across the Atlantic to western Africa in the 1960s (Menard et al. 2002; Chavance 2002) and are now deployed worldwide (Broadhurst 2000), particularly throughout tropical regions (Vendeville 1990).

At present, STs are responsible for an estimated annual global shrimp catch of 3.1 million metric tons (MMT) (FAO 2011; Asche et al. 2012). When combined with the estimated annual production of 3.5 MMT from aquaculture, shrimp are the most economically valuable internationally-traded seafood commodity, accounting for 17 percent of the total value of traded fishery products (FAO, 2008). U.S. shrimp production amounts to 100 thousand metric tons (KMT) (Mukherjee et al. 2011; Voorhees et al. 2011). With imports of an additional 500 KMT, the United States is the largest consumer and importer nation of shrimp in the world (Anderson 2003; FAO 2008). In 2010, annual U.S. consumption of shrimp was 4 pounds (1.8kg) per capita, compared to 2.7 pounds (1.2kg) of canned tuna and 5.0 pounds (2.3kg) of fillets and steaks of aggregated fish species (Asche et al. 2012). From 2005-2009, 80% of the total shrimp landings in the United States were from the Gulf of Mexico (GOM) (Mukherjee et al. 2011;

Voorhees et al. 2011) and 7% from the southeast Atlantic (~9KMT) (Voorhees et al. 2011). The remaining 13% of total landings were attributed to Northern Shrimp *Pandalus borealis* and Ocean Pink Shrimp *Pandalus jordani* that occur in the cold waters of the North Atlantic and North Pacific, respectively. The GOM ST fishery targets Brown Shrimp *Farfantepenaeus aztecus*, White Shrimp *Litopenaeus setiferus,* and Pink Shrimp *Farfantepenaeus duorarum*. In 2010, the GOM shrimp production was led by Texas (34.97 KMT), followed closely by Louisiana (33.66 KMT), the west coast of Florida (4.99 KMT), Alabama (4.54 KMT), and Mississippi (1.86 KMT) (Voorhees et al. 2011). The ST fishery operates year round in the GOM, with highest effort occurring May through December (Nance 1993a). The U.S. ST fishery can be separated into two components with the majority of boats today belonging to the inshore component and the remaining to the offshore segment. My thesis research focused on the offshore GOM ST fishery (OGSF) consisting of a variety of shrimp species that varied by geographic location. The majority of Brown Shrimp catch from offshore waters occurs primarily off the coasts of Texas and Louisiana in depths between 36.5–73 m (NMFS, 1999). White Shrimp are typically caught in waters of about 18 m in the same areas. Pink Shrimp are caught in waters of about 64 m, predominately off southwestern Florida in the winter months.

State agencies manage their respective fisheries that occur within each state's territorial waters. Federal agencies manage waters starting at the edge of each state's territorial waters out to 200 nautical miles limit of the exclusive economic zone (EEZ) (NMFS 2007a). Under the Magnuson Stevens Fishery Conservation and Management Act (MSA), eight regional management councils are given the authority to manage federal fisheries in the EEZ. The Gulf of Mexico Fishery Management Council (GMFMC), the South Atlantic Fishery Management Council (SAFMC), and the corresponding states manage the GOM and the South Atlantic Bight (SAB) ST fisheries.

The U.S. ST fishery was an open access fishery with historical estimates of up to 20,000 vessels actively capturing shrimp in state and federal waters (NMFS, 1998). No total allowable catch (TAC) is set on the exploited shrimp species because landings vary mostly as a response to environmental conditions and shrimp life history that includes short life spans (~1 year) (Nance 1993 a,b). Since December 2002, U.S. vessels have been required to apply for an annual federal shrimp permit. In 2006 the GMFMC created an Ad Hoc Shrimp Effort Working Group (SEWG) to explore possible effort targets for the ST fishery of the GOM EEZ (Nance et al. 2008). The SEWG was directed by the GMFMC to determine the minimum level of fishing effort necessary to achieve maximum sustainable yield (MSY); and further, the level of fishing effort that would produce the maximum economic yield (MEY), defined as the level of landings that would maximize profits to the harvest sector (Nance et al. 2008). This distinction between MSY and MEY is important since MSY and associated cost of effort at MSY (Emsy) may not represent the level of effort needed to maximize profits to the fishery.

The economic impact and value of the U.S. ST industry is reflected by the nickname "pink gold" as shrimp were called in the mid-1990s when U.S. ST fishery profitability peaked. Diamond (2000) reported that the U.S. ST fisheries of the GOM and the South Atlantic Bight (SAB) were the most valuable fisheries in the southeastern U.S., generating landings worth about $500 million annually (NMFS 2003a).

Fishing effort for the GOM ST fishery is reported as number of "days fished", and is calculated as the number of 24-hour days that a vessel actually fishes (Nance et al. 2008). For example, if a vessel fished 11 hours one day, 13 hours the next day and 10 hours the third day, the fished days would be 1.4 [i.e., (11hr+13hr+10hr)/24hr=1.4 days]. ST fishing effort in the GOM increased markedly in 1976, and remained uniformly high (200,000 nominal days fished per year) through 2002 (Gallaway et al. 2003). A downward trend began in 2002, and continued through 2005 (Nance et al. 2008), with effort reaching a 40-year low of 63,075 nominal days fished in 2008 (Figure 1; Nance, personal communication). In 2005 the GMFMC acknowledged the serious economic problems faced by the U.S. shrimping industry in the northern GOM EEZ. To limit entry into the overcapitalized fleet, a temporary moratorium on new entries into the OGSF was proposed by the GMFMC in 2005 and approved by the U.S. Secretary of Commerce in September 2006 (Nance et al. 2010).

In 2008 the U.S. GOM ST fishery was still in a pronounced economic decline and the methods used by the fleet to deal with low shrimp prices and high fuel costs varied considerably (Nance et al. 2008). To minimize costs, in some instances, vessel insurance policies were not renewed, crew shares were reduced, the number of trips taken was reduced, the duration of trips and the distances traveled to fishing grounds were reduced, and maintenance was deferred (Nance et al. 2008). Hart (2008) stated that "the reduced catches of the Tortugas Pink Shrimp fishery in recent years was purely economical, resulting from reduced fishing effort, attributed to the financial hardships currently experienced throughout the GOM commercial shrimp fishery".

The U.S. ST fishery decline resulted from a combination of lower prices for imported shrimp product and higher operating costs, most notably increasing fuel costs (Nance et al. 2008; Hart 2008). Competition with aquaculture shrimp placed downward pressure on the wild-caught shrimp prices. With wild shrimp from the GOM comprising only 14% of the domestic shrimp market, imports of farm raised shrimp from Thailand, China, Vietnam and South America have heavily impacted U.S. shrimp markets (Haby et al. 2003). In 2002 specifically, competition was exacerbated when the European Union raised tariffs on imported shrimp from Thailand, leading to increased exports from Thailand into U.S. markets, and drastic ex-vessel price reductions for U. S. wild-caught shrimp (Haby et al. 2003). The situation was so severe that in

2003 the U.S. government provided emergency disaster relief of \$17.5 million to GOM shrimpers (Diamond 2004).

The reduced ex-vessel price for GOM shrimp was accompanied by increased fuel prices for STs. This had considerable consequences for the OGSF since the fuel needed to tow the trawl gear continuously over the seafloor represents a large fraction of operating costs, as opposed to passive fishing gears such as gill nets, pots, longlines (FAO 2008), which drift in the current or are stationary. Krampe (2006) reported that the period from 1979 to 1998 was one of depressed oil prices; then, with global demands increasing from 1998 to 2003, the price of oil doubled from 15 USD to 30 USD per barrel, and then doubled again to 60 USD by 2005. This increase of 400% in fuel prices over a 7-year period coincided with the reduced profitability of the U.S. ST fishery. The results of a MEY sensitivity analysis for the OGSF suggests that for every \$0.25 decrease in the price of shrimp or increase in the price of fuel, the MEY decreases by between 2.8 and 3.5 million pounds and the associated effort at MSY (E_{msy}) decreases by between 5200 and 6400 days fished (Nance et al. 2008).

Environmental disturbances also contributed to the rapid decline of the U.S. GOM ST industry. Hypoxia, a low oxygen phenomenon that results in a recurring dead zone in the GOM, can potentially impact shrimp aggregations, production, and size distribution, reducing the supply of domestic wild-caught shrimp (Nance et al. 2010). In addition to hypoxia, a 2007 report to the U.S. Congress concluded that hurricanes Katrina (August, 2005), Rita (September, 2005), and Wilma (October, 2005) caused substantial damages and losses to the harvesting and processing sectors of the GOM ST industry, which accelerated the reduction in fleet size and effort (Nance et al. 2010). The observed reductions in effort (Figure 1) coincided with increased capture per unit effort (CPUE) (Figure 2) for the OGSF (Nance et al. 2008). The increase in CPUE suggested that the shrimp may be available for harvest if shrimpers were financially able to target them (Hart 2008).

Historically, NMFS has used a virtual population analysis (VPA) model developed by Nichols (1984) to assess the status of the GOM shrimp stocks. VPA model result indicated that overfishing was not evident in any of the GOM shrimp stocks from the mid-1980s (Klima et al., 1990; Nance 1993a) until 2008 (Hart et al. 2010). The NMFS now assesses the GOM Pink Shrimp stock with Stock Synthesis (SS-3) (Hart 2012 a,b,c), a widely used, peer-reviewed stock assessment model (Methot 2009; Schirripa et al. 2009; Methot and Wetzel 2013). This new modeling approach allows for the inclusion of fisheries-independent data into the stock assessment. Due to the improved output of the SS-3 Pink Shrimp stock assessment in comparison to VPA output, it was subsequently decided that NMFS should also conduct the White Shrimp and Brown Shrimp stock assessments using the SS-3 model. The SS-3 model outputs reveal an increasing spawning biomass and recruitment in recent years for Brown Shrimp, White Shrimp, and Pink Shrimp, and a decreased trend in fishing mortality (F). Hart et al. (2012a,b,c) reported that there continues to be no indication that the shrimp stocks of the GOM are overfished, or that overfishing is occurring.

The vessels and gears used by the OGSF are not homogenous but broad generalizations can be made about certain gear characteristics used in this fleet. GOM shrimp vessels are generally larger than 21.3 m, have freezer storage capacity, and are of steel construction (Scott-Denton et al. 2012). The STs are held open by the drag on large planning surfaces called boards or doors (Watson et al. 2006), and in this fleet, doors are generally made of wood (Scott-Denison et al. 2012), with aluminum or steel doors occurring much less frequently (Watson 1999). Primary trawl characteristics (Figure 3) such as headrope length (16.9 m), codend material (nylon), trawl extension (none), chaffing gear (mesh), and lazy line rigging (elephant ears), are similar throughout the GOM for all target species (Scott-Denton et al. 2012). Typically the try-net, a small sampling trawl used to test for shrimp abundance in real time (Watson et al. 1999), has a head rope length of 3.66 m (Scott-Denison et al. 2012). Trip length averages (not days fished per trip) are 13.8 ± 10.7 s.d. days, and average individual tow times are 5.2 hr ± 2.2 s.d. in the GOM (Scott-Denton et al. 2012).

Bycatch

Many authors have defined bycatch and examined its detrimental effects on regional and global scales (Alverson et al. 1994; Hall 1996, Greenstreet et al. 2000; Hall et al. 2000; Murawski et al. 2000; NRC 2002; Chuenpagdee et al. 2003; Diamond 2004; Kumar et al. 2006). Hall et al. (2000) defined bycatch as "the portion of the catch that is discarded at sea dead or injured to an extent that death is the result". Hall et al. (2005) later redefined bycatch as the fishing mortality resulting from the catch that is not accounted for in the landed catch. This definition equates to the discard mortality, a well-publicized consequence of commercial fishing operations, and represents the focus of the vast majority of the quantitative literature on bycatch levels. Davies et al. (2009) defined bycatch as catch that is either unused or unmanaged and noted that in many ST fisheries, much of the catch other than shrimp has traditionally been considered as bycatch and was usually discarded. Patrick et al. (2013) defined bycatch as fish that are captured in a fishery but not retained for sale or personal use. Reasons for discarding catch vary, but some general reasons include: the species is protected by regulation, the fish is not marketable, lack of storage space onboard the boat, high grading for higher valued species, or the fisherman's quota has already been reached (Patrick et al. 2013).

In addition to the issue of bycatch fishing mortality are concerns over the more complex ecological impacts that bycatch motality may have on the trophic structures of communities (De Groot 1984, Jones 1992, Dayton et al. 1995, Broadhurst 2000). The indirect effects of bycatch may also impact target species population dynamics through changes in predator–prey relationships which may have economic consequences that are difficult to predict (Hall et al. 2005). Like the majority of trawls, conventional STs are poorly selective fishing gears (Saila 1983; Broadhurst 2000; Diamond 2004) and as a result, many authors have addressed the detrimental effects of trawling in terms of a reduction in biodiversity, shifts in community structure, disruption of the food web, waste, user conflicts, and mortality of undersized target and non-target species (Alverson et al. 1994, Hall 1996, Greenstreet et al. 2000; Hall et al. 2000; Murawski et al. 2000; NRC 2002; Chuenpagdee et al. 2003; Diamond 2004; Kumar et al. 2006). Furthermore, STs contact with the seafloor can disrupt benthic ecosystems in shallow as well as deep-sea waters (Watson et al. 2006).

The capture of bycatch in STs is an important concern for fishermen, fishery managers, and environmentalists (Warner 2004; Alverson et al. 1996). Fishery managers first noticed finfish bycatch in the GOM ST fishery in the 1930s, but until the 1980s, most researchers concluded that ST bycatch had little effect on non-target fish populations (Diamond 2004). This lack of effect was thought to be because (1) bycatch fishes are mostly juveniles and natural mortality is so high in the juvenile stage that most bycatch fish would not have survived to adulthood, (2) bycatch had been occurring for decades without major changes in species composition or numbers taken, and (3) environmental factors were thought to have a stronger influence on populations than bycatch mortality. Some authors believed that bycatch could actually be beneficial to fish stocks by reducing competition for food, thus increasing the sizes of fish that were left through density-dependent compensation (Lunz et al. 1951; Gunter 1956; Bryan et al. 1982; Diamond 2004).

By the mid-1980s it was recognized that ST bycatch was extremely large and of genuine concern. The MSA was amended in 1990 to include a requirement that bycatch be avoided or, where it cannot be avoided, that bycatch mortality be minimized. The amendment also mandated the creation of a bycatch research program to assess the impact of incidental harvest by the ST fisheries, including the nature and extent of bycatch, its effects on fish stocks, and ways to reduce ST bycatch (Hoar et al. 1992; Diamond 2004). Since the 1980s, bycatch in the GOM ST fishery, first of sea turtles and more recently of finfish, has been one of the most controversial and intractable fishery management problems in the region (Diamond 2004). Broadly speaking, the bycatch challenge for ST fishery is threefold: First, ST fisheries are often prosecuted in areas where sea turtles are present and vulnerable to capture by the trawls (Chan et al. 1988; NRC 1990; Stobutzki et al. 2001). Second, the weight of the bycatch is often greater than the weight of shrimp (Warner 2004). Third, there can often be a significant bycatch of commercially important target species from other fisheries (Gallaway et al. 1999).

The incidental capture of sea turtles by ST fisheries was identified as the most important anthropogenic source of mortality in juvenile, sub-adult, and breeding sea turtles in U.S. coastal waters (Caillouet et al. 1996). Sea turtle bycatch falls under two pieces of legislation—the Endangered Species Act (ESA) and the MSA. All six sea turtle species that occur in U.S. waters (Green *Chelonia mydas*, Loggerhead *Caretta caretta*, Olive Ridley *Lepidochelys olivacea*, Kemp's Ridley *Lepidochelys kempii*, Leatherback *Dermochelys coriacea*, and Hawksbill *Eretmochelys imbricata*) are listed as either threatened or endangered under the ESA and afforded federal protection in all U.S. waters. The MSA specifies that bycatch-related mortality of non-target fish should be minimized, and sea turtles are protected under the ESA and there capture is prohibited.

According to Alverson et al. (1994), the top 20 highest discard ratios in the world (the ratio of target species to discards, by weight) are dominated by bottom trawl fisheries, where one-fifth or less of the catch is typically retained (Watson et al. 2006). The mortality of large quantities of bycatch from STs has attracted worldwide attention over the last 30 years (Saila 1983; Andrew et al. 1992, Alverson et al. 1994; Kennelly 1995; Broadhurst 2000). In 1994, ST bycatch was estimated by Alverson et al. (1994) to be around 11.2 MMT worldwide making ST fisheries the highest producers of discard, and responsible for over 27 percent of estimated total global discards (Keller 2005; FAO 2005). Chaboud et al. (2011) recently estimated that worldwide ST discards represent 9.5 MMT, which is equivalent to 1/3 of world total fisheries discards.

Harrington et al. (2005) estimated 1.06 MMT of marine fish were discarded in 2002 in all U.S. fisheries, making the United States one of the highest discard nations at that time (Scott-Denton et al 2012). Total ST bycatch for the United States is estimated at 100 – 400 KMT annually (Keiser 1977; Nichols et al. 1990), primarily consisting of juvenile fishes, adults of small fish species, and many species of invertebrates (Diamond 2004). The FAO in 2005 reported 480 KMT of ST bycatch for the United States. Alverson et al. (1994) indicated that in the western North Atlantic Ocean, the penaeid ST fishery had the highest ratio of bycatch to target species, with 10 kg of bycatch to 1 kg of shrimp, and 8 kg of bycatch to 1 kg of shrimp in waters of the GOM wich represented 84% of the catch by weight and 71% by number between 1992 and 1997, which was before bycatch reduction devices (BRDs) were required in federal waters.

The consequences of killing and discarding huge quantities of juveniles of commercially valuable fish species are of particular concern (FAO 2011), since this loss is thought to reduce the recruitment, biomass and yield of stocks that form the basis of other commercially and recreationally important fisheries (Broadhurst 2000). Bycatch in STs is a significant source of fishery-induced mortality for several managed finfish species in the southeastern U.S. (Pellegrin 1982, Alverson et al. 1994; Scott-Dentonet al. 2012) and this can be a challenge to stock rebuilding programs (Diamond 2000). A total of 185 species were identified in the catch of the

OGSF with finfishes dominating the bycatch. The average composition of the ST catch was fish bycatch at 57% or 19.5 kg per hour of towing (kg/h), followed by shrimp catch at 29% (9.9 kg/h), crustaceans bycatch at 7% (2.4 kg/h), invertebrates bycatch at 5% (1.8 kg/h), and debris at 1% (0.5 kg/h), for an overall (total catch) CPUE of 34.3 kg/h (Scott-Dentonet al. 2012). In terms of species composition, Atlantic Croaker *Micropogonias undulatus* represent 16% (5.4 kg/h) of the total catch, grouped finfish (Black Drum *Pogonias cromis*; Cobia *Rachycentron canadum*; King Mackerel *Scomberomorus cavalla*; Lane Snapper *Lutjanus synagris*; Red Drum *Sciaenops ocellatus*; snapper *Lutjanus* spp. (other than Red Snapper *Lutjanus campechanus*); grouped sharks (order Selachii); Southern Flounder *Paralichthys lethostigma*; Spotted Seatrout *Cynoscion nebulosus*; Spanish Mackerel *Scomberomorus maculatus*; Vermilion Snapper *Rhomboplites aurorubens* and Gulf Flounder *Paralichthys albigutta)* account for 27% (9.4 kg/h) of the total catch, followed by Brown Shrimp at 14% (4.8 kg/h), White Shrimp at 11% (3.7 kg/h), crustaceans at 7% (2.4 kg/h), sea trouts at 6% (2.0 kg/h), invertebrates at 5% (1.8 kg/h), Longspine Porgy *Stenotomus caprinus* at 4% (1.4 kg/h), and Pink Shrimp at 4% (1.3 kg/h). All other species accounted for 6% (2.0 kg/h) of the total weight (Scott-Denton et al. 2012). GOM catch proportions are presented graphically in Figure 4.

One of the bycatch fish species of great concern in the OGSF is the Red Snapper, a species with large directed commercial and recreational fisheries. On average, an estimated 25–30 million juvenile Red Snapper are caught annually as bycatch in the OGSF (Ortiz et al. 2000). Red Snapper bycatch is an especially contentious issue because strict regulations on directed Red Snapper fisheries (commercial and recreational) have been in place since 1990 (Goodyear 1995), when a stock assessment showed that 90% of the mortality on age 0 and 1 Red Snapper resulted from shrimp trawl bycatch (Goodyear et al. 1990; Diamond 2004; Wells et al. 2008).

Atlantic Croaker is one of the most commonly caught bycatch species in STs, ranking second by number in the GOM and third in the SAB (NMFS 1995). In the GOM, surveys conducted since 1972 show that Atlantic Croaker density and biomass have significantly decreased since 1990 (Diamond et al. 1999). Though natural mortality of larvae and juveniles and not bycatch mortality of late juveniles was considered to be the most important factor affecting Atlantic Croaker populations, a reduction of about 35% in either the late juvenile or the adult mortality rate in the Gulf would be enough for this population to recover, or at least to noticeably slow population declines in the Gulf of Mexico (Diamond 2000). BRDs that are required in the GOM may also help achieve these reduction targets (Diamond 2000), as Atlantic Croaker are amenable to release using BRDs (Watson et al. 1993; Diamond 2000).

Some species of fish are more vulnerable to overfishing then others, and sharks are particularly so. Most sharks have life histories that are characterized by slow growth, late sexual maturity, few offspring produced per litter, and long life spans (Camhi 1998; Stevens et al. 2000; Musick et al. 2000). These life history characteristics present special problems for shark fishery management (Holden 1974). Some U.S. populations of sharks have declined by as much as 85% since the late 1970s (Camhi 1998). Generally, these declines are attributed to direct fishing pressure from commercial and recreational fisheries, but effects from other fisheries that encounter sharks as bycatch also play a role (Barker et al. 2005). On April 26, 1993, NMFS implemented the nation's first federal fishery management plan (FMP) for sharks, covering U.S. shark fisheries of the Atlantic Ocean, GOM, and Caribbean Sea (NMFS 1993). The FMP placed 39 species of sharks under management in federal waters and included commercial quotas, closed seasons, recreational bag limits, and a ban on shark finning (NMFS 1993; Hueter 1994). Hueter (1994) reported that the 1993 shark FMP did not fully address bycatch issues even though bycatch by commercial STs had been identified as a large source of sub-adult shark mortality (Camhi 1998; Stobutzki et al. 2002; Shepherd et al. 2005). At the time it was estimated that three times as many sharks were caught annually as bycatch by STs in the GOM than combined commercial and recreational shark landings in U.S. GOM and Atlantic waters (Parrack 1990). The status of small coastal sharks was later evaluated using several stock assessment methods and results suggest that these populations were generally healthy (Cortes 2002; Simpfendorfer et al. 2002; Burgess et al. 2005). Of the four species comprising the small coastal shark complex, only the stock of Blacknose Sharks *Carcharhinus acronotus* off the southeastern U.S. and GOM was determined to be overfished with overfishing occurring, and as much as 45% of the animal fishing mortality (38,626 individuals) of Blacknose Sharks was attributed to the GOM ST fishery (NMFS 2007b).

Management Options

There are different options for managing bycatch through the regulatory system, such as quotas, discard bans, mandatory use of bycatch, fishing effort reductions, spatial management and the use of BRDs. The use of caps or quotas to reduce bycatch can be classified under the management strategy of incentive/disincentive programs (Alverson et al. 1994). Incentives related to the ability to continue fishing, and disincentives including fishery closure, temporary loss of the right to fish, fines, and expulsion from the fishery and/or reduction of future quotas, are used to induce fishermen to make operational fishing choices that reduce bycatch. Oceana, an environmental, non-governmental organization, petitioned the U.S. Secretary of Commerce to "initiate rulemaking to establish a program to count, cap, and control bycatch in the nation's fisheries" (Oceana 2002). One of the specific requests detailed in the petition was to set bycatch caps or quotas, and to close fisheries when either the target species total allowable catch (TAC) or the bycatch quota is reached.

Other countries have used a variety of management measures to address bycatch issues in their respective ST fisheries. Namibia, located on the west coast of Africa, has completely banned bycatch in its EEZ (Hampton 2003). This ban requires that all bycatch be landed for conversion to fishmeal. A surcharge is also levied on the fisheries for fishmeal processing, which acts as an additional incentive to further reduce bycatch (Hampton 2003). According to Hall et al. (2005), it is important to recognize the distinction between a discard and bycatch ban. Whereas the discard ban only applies to species that have commercial value and are either undersized or for which a fisher does not possess quota, the bycatch ban requires that all species captured, irrespective of their value, be landed (Hall et al. 2005). It is understandable that Namibia would adopt such a strategy since, in many cultures, failure to make use of fish that are already killed is viewed as highly undesirable (Hall et al. 2005). This is particularly true for developing countries where the supply of adequate protein to the populace is a challenge and bycatch can provide an important food subsidy to those communities.

Guyana located on the north east coast of South America mandated landing of bycatch through legislation. All ST fisheries in Guyana are required to land 1 ton of bycatch per trip in order to obtain exemption from export taxation and a nominal fee payment (Gordon 1981; Clucas 1997). However, considering the history of overexploitation by fisheries, creating new markets for bycatch can be problematic. As species become substantially depleted, what was once bycatch soon becomes new acceptable targets, leading to further depletion and other ecological consequences (Hall et al. 2005).

Mandatory effort reductions for target species can be used to reduce bycatch. The International Council for the Exploration of the Sea (ICES) recommended fishing effort reductions to decrease bycatch in Danish and UK groudfish trawl fisheries (ICES 2002). In 2002 the U.S. National Research Council analysis of the GOM shrimp fishery indicated that effort could be reduced by almost 50%, while maintaining the same target shrimp catches and greatly reducing bycatch.

Another management option to reduce bycatch is to restrict trawling to locations and times known to have relatively small amounts of bycatch (time-area closures; Broadhurst 2000, O'keefe et al. 2013). Although there can be substantial variability in the timing and location of bycatch, analysis of bycatch records can often identify areas where closure has the potential to reduce bycatch (Hall et al. 2005). Ye et al. (2000) examined the temporal and spatial patterns in the catch to bycatch ratios for the Kuwait shrimp fishery. This analysis showed that a seasonal fishery closure from April/May to August, that was originally established to prevent overfishing and increase the size and market value of the target shrimp, also reduced bycatch. A more dynamic approach than closing areas permanently is hotspot reporting (Hall et al. 2005). Bering Sea fishers, for example, have voluntarily developed and implemented a real-time monitoring and information-sharing system to tell the fishing fleet about bycatch rates and hotspots for prohibited species (Gauvin et al. 1996). Observer data on catch and bycatch are transmitted electronically from participating vessels to a private contractor who analyzes the submitted data and provides estimates to participating vessels and companies of the spatial distribution of average catch rate per vessel for each 24-h period (Hall et al. 2005). These data allow individual vessels or company fleets to rapidly respond and avoid areas where bycatch of protected species is expected to be high (Hall et al. 2005).

In addition to using the regulatory system as a means to reduce bycatch, regulations can inadvertently create incentives to generate bycatch and discards (Hall et al. 2005). There are many cases where regulations enacted to try and ensure that target species were not overexploited led to discarding of the very species they were trying to protect. For example, when trip limits are imposed for one species, discards of other species can increase because fishers catch the limited species while fishing for others (NMFS 1998). Similarly, discarding occurs when a fisher does not possess quota for a particular species that is inadvertently caught

(Hall et al. 2005). Thus, the mixture of incentives and disincentives that are put in place with particular legislation may not be easily foreseen and may impact bycatch levels (Hall et al. 2005).

Bycatch reduction can also be achieved through gear selectivity. After decades of attention to maximize effectiveness and efficiency of fishing gear, technologists started to focus on more conservation-orientated goals during the last few decades (Kennelly et al. 2002). This focus began as a response to concerns over bycatch of large charismatic species (dolphins, turtles), but quickly broadened to address concerns over the discarding of less charismatic species, such as juvenile fish killed by STs (Kennelly et al. 2002). Fishing gear modifications to reduce bycatch have been a major focus of fisheries research since the 1990s, and these gear modifications have been a major approach to address bycatch issues throughout the world's ST fisheries (Broadhurst 2000; Diamond 2004). In the U.S., the efficacies of BRD designs have been evaluated by NMFS, state fishery agencies, Sea Grant agents, and university biologists using controlled comparison studies (e.g. modified nets versus unmodified nets) aboard research and commercial vessels (Diamond 2004). The successful development of BRD devices has led to mandatory use of both TEDs and other BRDs in U.S. shrimp fisheries. As stated previously, bycatch by ST fisheries can be broken down into 3 categories: turtle bycatch, finfish bycatch of non-commercially important species, and bycatch of commercially important species. Gear has been developed to address these three bycatch issues.

The directed harvest of all sea turtles was made illegal in U.S. federal waters with the passing of the ESA in 1973 (Moore et al. 2009). Efforts were made to reduce the incidental capture of sea turtles through the development and introduction of both hard and soft TEDs to the U.S. ST fishery on a voluntary basis during the 1980s (Watson et al. 1980; Tucker et al. 1997). The concept of the TED entails a physical barrier that prevents the turtle from entering the codend and facilitates subsequent release through a trap door (Tucker et al. 1997; Broadhurst 2000).

The V type vertical separator trawl, a form of soft TED was found to be effective in removing turtles but had limited acceptance amongst commercial fishermen because of reductions in shrimp catches of up to 60% (Broadhurst 2000). Due to multiple problems associated with soft versions of these designs, in particular fish and weed entanglement, the utility of hard grid TED designs was tested (Tucket et al. 2008). Hard TEDs (hereafter referred to as TEDs) generally consist of a metal separator grid that is installed in the trawl at an inclined angle (Figure 6; Tucker et al. 1997). Hard TEDs have been more successful when compared to soft TEDs (Broadhurst 2000) and their use has persisted through time. TEDs have been effective in reducing catches of turtles by up to 97% (Tucker et al. 1997; Broadhurst 2000), and their use on shrimp and flounder trawlers has been required since 1987 (Federal Register 1987) and 1996, respectively (Moore et al. 2009).

Watson et al. (1986) developed an early model TED called the 'NMFS trawl efficiency device' which consisted of a solid inclined grid placed anterior to strategically located side-escape windows, all encompassed within a steel frame. Although many fishers objected to its weight (40 kg) and size (91 × 114 × 76 cm), some voluntarily used this TED as a BRD in certain areas because of its ability to reduce catches of jellyfish (Broadhurst 2000). One of the most successful TED designs developed in the GOM was a declined, bottom-opening grid termed the 'super shooter' (Figure 7). It is effective in almost completely eliminating catches of turtles with minimal reductions of shrimp catch (Renaud et al. 1993; Broadhurst 2000). By 1990, TEDs were in widespread use throughout the ST fishery of the southeastern U.S. (Crowder et al. 1995; Raborn et al. 2012).

TEDs have now existed for over 30 years and there have been continual improvements to the design required for use by U.S. ST fisheries. Of particular importance was the 2002 regulation to increase the opening size of the escape hole of TEDs. Epperly et al. (2002a) suggested that roughly 62,300 loggerheads may have been killed each year, along with 2,300 leatherbacks, 20,000 Kemp's Ridley turtles, and 1,400 green turtles, prior to the 2002 regulations (Federal Register 2003). Interestingly, Epperly et al. (2002b) suggested that even with new TED size regulations, anticipated sea turtle mortality by U.S. STs may be on the order of 25,000 individuals per year. Mitchell et al. (2002) found no significant difference in shrimp catches in nets equipped with the new, larger-opening TEDs.

Though capable of significantly reducing turtle bycatch, the use of TEDs has historically been resisted by many in the fishing industries due to the associated costs, negative effects on gear performance and handling, and some loss of targeted shrimp (Tucker et al.1997; Broadhurst 2000). Estimates of shrimp loss (1%) associated with the use of the Super Shooter TED, a model commonly used in the OGSF, were derived from a study conducted by Renaud et al. (1993) from 1988 to 1990. A reanalysis of these data, in which the try-net effect was excluded, suggested that TED use could result in a 6% shrimp loss (Gallaway et al. 2008). The low finfish bycatch reduction (5% to 13%) associated with TEDs (Raborn et al. 2012), further contributed to TEDs not being fully embraced by industry. Early TEDs were bulky and cumbersome, and few shrimpers accepted the research findings of minimal shrimp loss (Tucker et al. 1997).

The nature by which TEDs were imposed also contributed to the initial rejection of TEDs by the U.S. shrimp trawling industry. The voluntary adoption strategy for an innovation such as TEDs allowed fishermen to mitigate the potential negative effect (e.g., shrimp loss) by altering or adjusting the TED, adjusting the adoption rate or even rejecting the TED all together (Morberg et al. 1994). In 1987, when TED use became mandatory on all commercial shrimp trawlers operating in U.S. federal waters (Moore et al. 2009), shrimpers no longer had control over the potential for negative impacts and they felt TEDs were harming their livelihood (Moberg et al., 1994). Consequently, suspicion and even hostility arose (Margavio et al. 1993, Tucker et al. 1997).

Since then, technological advancements for the prevention of turtle captures has not only improved the efficiency of the TED but also contributed to fish bycatch reduction. The use of various TEDs in the southeastern U.S. ST fishery has reduced the bycatch of sharks, rays (Watson et al. 1986; Mitchell et al. 1995; Engass et al. 1999, Raborn et al. 2012) and large fish (Tucker et al. 1997; Broadhurst 2000).

In 1990, concerns over ST bycatch on four key species of finfish, Red Snapper, Weakfish *Cynoscion regalis*, King Mackerel, and Spanish Mackerel, led to a large co-operative program between several research agencies to evaluate gear modification options (Hoar et al. 1992; Rulifson et al. 1992; Watson 1996). Watson (1996) reported that a total of 96 BRDs were considered and evaluated. Seventeen years later Scott-Denton et al. (2012) report that more than 150 BRD styles were developed by industry, scientists and gear specialists and evaluated through cooperative multi-year efforts. Due to the variety of fishing conditions and bycatch species, there is no single solution to achieve bycatch reduction and maintain target catches in the ST fishery (Robins-Troeger et al. 1995; Tucker et al. 1997). BRD research continues as an ongoing strategy to mitigate bycatch in the U.S. ST fishery.

BRD development for trawls has nearly always involved different types of physical modifications to improve gear selectivity (Kennelly et al. 2002). Depending on the species to be excluded and retained, these modifications range from simple changes of mesh sizes and materials (Broadhurst 2000; Gray et al. 2000; Kennelly et al. 2000) to the application of unique and often complicated BRDs (Broadhurst 2000; Kennelly et al. 2002). Despite the wide variety of modifications, most BRDs can be classified into two categories according to the basic theory and methods used to facilitate the escape of bycatch: BRDs can separate catches mechanically according to their sizes (e.g. rigid devices like the TED) or via differences in physiology and/or behavior of the species (e.g. like composite square-mesh escape panels) (Broadhurst 2000; Kennelly et al. 2002).

Previous studies have shown that escape of fish through BRDs is largely determined by species-specific responses to various tactile and visual stimuli (Wardle 1983; Watson 1989; Glass et al. 1995) as well as density, abundance and schooling behavior in the trawl (Watson 1989; Broadhurst et al. 1996a; Broadhurst et al. 1996b; 1999c). Divers from the NMFS Mississippi Laboratory observed that fish actively swam through the TED and maintained positions in areas of reduced water flow behind the TED, whereas shrimp were passively carried through the TED into the codend (Engass et al. 1999). In ST fisheries where bycatch is characterized by an abundance of small fish or fish of a size similar to the targeted shrimp (i.e. in many of the world's ST fisheries), BRDs that operate by exploiting behavioral differences between fish and shrimp may be effective (Broadhurst 2000), and differences in swimming ability between finfish and shrimp in trawls have been utilized in the southeastern U.S. ST fishery to reduce bycatch of finfish (Engass et al. 1999). To design an efficient species-selective ST, detailed knowledge of the behavior of fish and shrimp and other trawl performance parameters that influence behaviors is required (Watson 1989; Broadhurst 2000).

Kennelly et al. (2002) and Broadhurst (2000) reported that the most extensive development and evaluation of BRDs that function by exploiting behavioral differences between bycatch and shrimp occurred in the southeastern U.S. Exploiting behavioral differences is particularly important for BRDs that are to be used in areas where ST activities occur in turbid water conditions where visibility is reduced (Engass et al. 1999). Most BRDs rely on active exclusion, using the behavioral reactions of bycatch species to actively swim out of the net via escape windows or funnel openings (Tucker et al. 1997). While recognizing that solutions to bycatch often need to be tailored to specific fisheries and may differ between regions of the world (Alverson 1999; Bache 2002; Hall et al. 2005), efforts to improve ST selectivity have led to the development of a variety of BRDs. Some of these are discussed below.

Many ST BRDs are relatively simple in concept and design. One such BRD consists of a horizontal opening cut out in the top of the codend. Experiments with this BRD demonstrate reduced total bycatch although mean target catches were reduced with no statistically significant loss of shrimp, (Wallace et al. 1994). Another option to reduce bycatch is to strategically position a square-mesh panel in the trawl. The use of the square-mesh panel BRD in North American fish-trawls led to the transfer and evaluation of similar designs across a number of ST fisheries throughout the world (Averill 1989; Larsen 1989; Karlsen et al. 1989; Valdemarsen 1986; Thorsteinsson 1992; Hickey et al. 1993; Broadhurst et al. 1994; Broadhurst et al. 1999; Broadhurst 2000). Species that are relatively fusiform and tend to occur in large schools (e.g. Sciaenidae and Sillagidae) may be successfully excluded using simple panels of square-mesh or other BRDs that incorporate small openings in the top or sides of the trawl (Broadhurst 2000). In a series of experiments conducted under commercial conditions, Broadhurst et al. (1994, 1995, 1996a, 1996b, 1997) tested a variety of square-mesh designs at different locations in the codend and examined the effects of operational factors on their performance (Broadhurst et al. 1999b). These studies showed that very small panels of square mesh strategically located in the tops of the anterior sections of codends significantly reduced large quantities of bycatch that included non-target individuals and juveniles of commercially and recreationally important species with no significant reduction in catches of King Shrimp *Penaeus plebejus* (Broadhurst 2000).

The Fisheye is another simple BRD design, which consists of a welded steel, pyramid-shaped frame that is inserted in the top anterior section of the codend. It was designed to allow fish to orient into an area of reduced water flow (inside the fisheye) and escape through an opening at the base of the BRD (Harrington 1992; Harrington et al. 1995; Watson 1996; Watson et al. 1996; Rogers et al. 1997; Broadhurst 2000). The Fisheye BRD shrimp loss was estimated to range between 3% and 7% depending on its location in the trawls (GMFMC 1997), while bycatch reduction was estimated to be 28% (Wallace et al. 1994).

The BRDs discussed above are simple in design while others involve significant and often complicated alterations to the geometry of the trawl, such as the inclusion of various guiding funnels combined with additional openings, panels of mesh, and/or rigid components (Broadhurst 2000). As previously noted, more than 150 BRDs have been described in the literature (Scott-Denton et al. 2012), below I discuss a few of the more complex BRDs that were evaluated since the 1980s (Watson et al. 1986).

Watson et al. (1990) developed and assessed several BRDs characterized by guiding funnels and small-mesh panels located immediately anterior to the codend. These BRDs directed water and slower-moving shrimp into the codend and allowed fish to swim forward and out through strategically located escape exits. In 1984, researchers with NMFS at the Mississippi Laboratory developed the first BRD that employed a funnel with escape openings positioned around it (Broadhurst 2000). The principle was to provide a stream of fast flowing water through the funnel to carry shrimp back into the codend and reduce flow around the funnel, guiding fishes into the area of the escape opening. One modification, termed the 'finfish separator device' (FSD) consisted of two funnels sewn inside the codend, terminating anterior to a 'deflector grid'. This latter device was designed to generate visual and tactile stimuli for fish, directing them to large, radially located openings separated by lateral supports (Watson et al. 1990). The FSD was effective in reducing the numbers of fish with no significant reduction in catches of shrimp. However, its performance varied greatly among different geographic areas, the size of individual species encountered, and their swimming abilities. In addition, the size of the BRD, combined with a potential for large objects to become meshed in the funnels, meant that few fishers were willing to adopt it as part of their normal commercial operations (Broadhurst 2000).

Another popular BRD that uses a funnel is the Jones/Davies BRD, which has four windows to provide an escape path for fish while a funnel keeps shrimp away from the windows. The reduced water flow around the windows acts as a physical cue to guide fish out of the trawl. Experiments with the Jones/Davies BRD have achieved reduction in juvenile Red Snapper bycatch mortality ranging from 52 to 67%, (Watson et al. 1999). Other funnel-type BRDs include the 'expanded mesh design' and 'extended funnel design'. These BRDs are similar to each other and comprise guiding funnels surrounded by larger square-shaped mesh located anterior to the codend (Harrington et al. 1995; Watson 1996; Watson et al. 1996). These two BRD designs were based on the original FSD and developed to direct shrimp into the codend while allowing fish to swim forward and escape through the larger, radially located square mesh (Broadhurst 2002). Variations of these designs were evaluated in areas throughout the southeastern U.S. (Rulifson et al. 1992; Wallace et al. 1994; Harrington et al. 1995). Rulifson et al. (1992) tested three BRDs similar in concept to the extended/expanded mesh funnel designs off the south Atlantic coast. While these BRDs were effective in facilitating the escape of some individuals of particular species, only one design significantly reduced total bycatch biomass, and the authors concluded that the designs needed to be refined on a species-specific basis

(Broadhurst 2000). The composite mesh panel (CMP) is a variant of a funnel-type BRD which is less complicated in design and is the newest addition to the suite of approved BRDs in U.S. federal waters. Fishery-dependent data collected during certification trials of the CMP in combination with a cone fish deflector attained a total fish bycatch reduction of 51.3% with an 8.2% shrimp reduction rate (Foster 2011). Similarly the CMP in combination with the square mesh panels placed in the codend showed a total fish reduction of 49.9% with a 1% shrimp reduction rate (Foster 2010). Both CMP gear combinations with either the cone fish deflector or the square mesh panel showed reducd captures of Atlantic Croaker (64.3%, 56.4%) and Longspine Porgy (22.2%, 14.1%), respectively.

The last BRD design discussed here that relies on funnels and escape panels is the 'radial escape section' (RES), which is based on the FSD design, and was modified and tested in several ST fisheries (Valdemarsen 1986; Averill 1989; Conolly 1992; Schick 1992). Variations of the RES design were successful in reducing the bycatch of individual species by up to 100% in Norway (Valdemarsen 1986), 77% in New England (Averill 1989) and 48% in Brazil (Conolly 1992), with shrimp losses of 53%, 14% and 27%, respectively (Broadhurst 2000). Although these results for bycatch and shrimp were comparable to those from other BRDs developed for these fisheries, Averill (1989) suggested that in addition to a loss of commercial shrimp, the main limiting factor of the RES was the complexity involved in its rigging (Broadhurst 2000).

Beyond alterations to the trawl body, a novel gear modification to reduce bycatch was the design of a trawl that included electric arrays in the footrope and lower belly which produced pulses of current (3 V at a rate of 4–5 pulses per second) (Seidel 1969; Seidel et al. 1978). These electric stimuli resulted in shrimp contracting their abductor muscles, propelling them vertically into the net, and some fish exhibiting a fright reaction horizontally away from the trawl. While the concept of electric trawls was considered technically feasible, high costs and practical limitations meant that the design was not fully developed for commercial testing or application (Watson et al. 1990; Broadhurst 2000).

BRDs were required in the late 1990s by NMFS to reduce the finfish bycatch, especially for overfished species such as Red Snapper in the GOM (GMFMC 1997), and Weakfish and Spanish Mackerel in the SAB (SAFMC 1996). BRDs have been required in Federal waters of the SAB since 1997, the western GOM since 1998, and the eastern GOM since 2004 (Federal Register 2004). Potential BRD designs are certified by NMFS, based on criteria set forth in the revised and consolidated BRD testing manuals and certification requirements for the GOM and SAB ST fisheries (NOAA 2008b). Once certified, effectiveness of BRD designs are periodically evaluated using observer data (Scott-Denton et al. 2012). Only three BRDs were found to be appropriate for development and testing under commercial ST conditions prior to 1996 (Watson 1996). Today four BRD designs are currently certified (or provisionally certified) for use in federal waters of the GOM and SAB ST fisheries: the composite panel, the extended funnel, the fish-eye, and the Jones/Davis (and modified Jones/Davis) (NOAA 2008a). An additional design, the expanded mesh BRD, is certified for use in the SAB ST fishery only.

BRDs have been beneficial in reducing bycatch in the GOM and SAB ST fisheries, but there are substantial drawbacks associated with their use. First, the use of BRDs has imposed additional costs on shrimp vessel owners due mainly to a loss of shrimp from their trawls (Gillig et al. 2001). Most studies found that bycatch reduction using BRDs was variable and depended not only on BRD design, but also on the placement of BRDs in the trawl, individual fishing practices, and fishing conditions (Broadhurst 2000).

For example, the Jones/Davis BRD exhibits variable bycatch reduction efficiency, which is affected by the manner in which the captain operates the vessel. One variable that contributes to these different results is net surge, which occurs when the vessel's velocity is reduced and the forward motion of the bag continues with water flowing forward towards the opening of the trawl (Engass et al. 1999). When this happens, fish that are positioned near the openings of the BRD are displaced. When the net is pulled forward again, the flow into the trawl increases and fish that escaped the BRD fail to regain position back inside the trawl (Engass et al. 1999). With the area around the opening now free of fish, others typically moved into the space previously occupied by the displaced fish. Therefore multiple surge events tend to increase the efficiency of the Jones Davis BRD. Furthermore, movements of fish through the escape openings were generally low and random during towing, except for catfish, which always showed a strong escape response (Engass et al. 1999). Haul back procedures can vary between vessels, which may in part explain the documented vessel-dependent escape rates for different BRDs. It is preferable that escapement occurs as soon as fish enter the escape area during towing. Such continuous escapement may reduce the possibility of extra bycatch mortality attributed to predation and displacement (Workman 1999). As previously noted, escapement was mainly observed during slowdown prior to haul back, i.e. in situations when water flow inside and outside the escape opening was nearly equal.

Bycatch reduction of juvenile Red Snappers has been a major focus in guiding the development of BRDs. Originally, certification for BRD designs in the GOM required a reduction of age-0 and age-1 Red Snapper bycatch mortality of 44% relative to the total ST fishing mortality evaluated for the period 1984 to 1989 (Federal Register 1998). Studies have shown that Red Snapper, which orient to structure (i.e. align themselves to rocks piles and reefs and maintain that position), are very difficult to remove passively from nets with BRDs because of this behavior (i.e., they align themselves to the net) (Engass et al. 1999). Based on the 1998 NMFS observer program aboard commercial vessels, it was estimated that about 23% of juvenile Red Snapper escaped from nets with certified BRDs, compared to control nets (Nichols 1999;

Diamond 2004). It was hoped that further reductions would occur as fishermen became more familiar with BRDs, so a projected 50% overall reduction of Red Snapper bycatch was assumed in 1999 to set the TAC of Red Snapper directed fisheries at 4.13 MT annually between 2000 and 2005 (RFSAP 1999). This estimate included data from Fisheye BRD placement in a particular section of the codend that has since been disallowed (Diamond 2004). Red Snapper bycatch reduction improved to 41% when those particular Fisheye BRD data were removed from the analysis (Diamond 2004). Still, BRDs have not achieved the 50% reduction of juvenile Red Snapper bycatch anticipated by the NMFS (1995) (Engass et al. 1999; Woodward et al. 2003).

The 2001–2003 ST onboard observer program showed that bycatch reduction levels have declined over time, and averaged only 11.7% for Red Snapper and 16.5% for all finfish species combined (Foster et al. 2004). The reason for the observed decrease in bycatch reduction is thought to be that fishermen modify their nets or change their practices to reduce loss of shrimp, which also reduces the efficiency of BRDs (Foster et al. 2004). An additional problem with current TEDs and other BRDs used in the U.S. ST fleet may be the inefficiency of these devices to reduce small elasmobranch bycatch. Brewer et al. (2006) concluded that BRDs had limited effect on bycatch of elasmobranches in an Australian ST fishery. Similarly, in the United States, an evaluation of a 30.5 cm x 12.7 cm fisheye BRD found that it was ineffective in reducing the number of sharks captured (Belcher et al. 2010).

Today there are only four BRDs that are certified for use in the OGSF and innovations in technological designs that further improve the selectivity of OGSF are necessary. Reducing the bycatch mortality of both large and small fishes through the gear development continues to be a priority for not only managers of this industry but for the industry itself. The objective of my thesis research was to evaluate a new TED design, the trash and turtle excluder device (TTED, Figure 8) in the OGSF.

The TTED is based on the super-shooter TED design but there are two major differences between the gears: (1) decreased spacing between the deflector bars in the TTED (5 cm) (Figure 8) relative to the TED (10.2cm) and (2) use of flat bars (6 mm width) instead of round bars (12.6 mm diameter). The reduced bar spacing of the TTED, as compared to the TED, may exclude more fish from entering the codend and result in reduced bycatch. Flat bars may improve water flow through the TED, towards the codend, since it encounters less resistance from the 6.3mm wide flat bars then it does from the 16mm wide round bars. Increased turbulence ahead of the TED can lead to deflection of water towards the opening, blowing open the flaps of the TED and resulting in shrimp loss.

The main advantage of the TTED is that it may considerably reduce the capture of large organisms. In preliminary work conducted in French Guiana, the TTED resulted in a 20-30% total bycatch reduction without significant target shrimp loss for the ST industry (Nalovic et al. 2010). Indeed the shrimp to bycatch ration in French Guiana is 1 to 10 and approximately two tons of bycatch species ranging from small invertebrates to large pelagic fish are thrown back to sea by each trawler daily (Léopold 2004). Experiments with the TED showed small reductions in total bycatch and the industry sought improvements in the TED performance (Duffaud et al. 2011) Based on this the French Guiana Regional Fisheries Committee in partnership with the WWF began experimenting with reduced bar spacing TEDs, including the Trash and Turtle Excluder Devise (TTED)—"trash" is a common term for bycatch in French Guiana. The TTED improved the selectivity of the original TED and was voluntarily adopted by the industry in March 2008, becoming mandatory by government decree in January 2010 (Duffaud et al. 2011). The TTED design may contribute to improved selectivity of the OGSF. The goal of my thesis research was to compare the shrimp and bycatch capture of a TTED to a standard TED under typical fishing operations onboard commercial ST vessels in the GOM and SAB using the sampling method described by the NMFS BRD evaluation protocol (NOAA 2008a).

I tested the following hypotheses:

Target (shrimp) catch:

H_o: The shrimp retention of the TTED is not different to the shrimp retention of a TED

H_a: The TTED shrimp retention is not equal to the shrimp retention of the TED

Fish bycatch:

H_o: The fish bycatch retention of the TTED is not different from the fish bycatch retention of the TED

H_a: The fish bycatch retention of the TTED is less than the fish bycatch retention of the TED

CHAPTER 2: MATERIALS AND METHODS

Data Collection Methodology

Comparative tows of the TTED and TED were conducted during the summer of 2012 (May-August) and continued in the fall of 2013 (September-December), allowing me to collect data from seasons with potentially different bycatch compositions. Data were collected using the NMFS U.S. Gulf of Mexico and Southeastern Atlantic Otter Trawl and Bottom Reef Fish Fisheries Observer Training Manual, which I will refer to as the NMFS observer protocol. Data collection occurred on five fishing trips, one of which was in waters of the U.S. South Atlantic Bight (in 2012), two in offshore waters of the northeastern GOM (one in 2012, one in 2013), one in offshore waters of the northwestern GOM (in 2012) and finally, one in waters in and around Key West, FL (2013). Consistent with past gear research in the GOM, the mouth of the Mississippi River was used as a dividing line between the eastern and western GOM (Gallaway et al. 2008). Trips left from and returned to fishing ports of Darien GA, Freeport TX, and Pascagoula MS (Figure 9).

Shrimp trawl vessels equipped to tow two pairs (Figure 3) of twin trawls (image of single pair, (Figure 5) simultaneously, were used as these allow for an experimental trawl (with TTED and no BRD) to be compared directly to a control trawl (with TED and no BRD). While variability in fishing conditions between tows may affect catch and size distribution of catch from the trawls being compared, the pairing of the trawls tends to control, to a large extent, between-haul variability and also variability resulting from alterations to the normal trawl configuration. The trawls used in the experiment were the two outboard trawls following Mitchell et al. (2002) since both vessel wash and the try-net may influence catches of the inboard trawls (Watson et al. 1999).

The TED design selected for the control trawl was the bent-bar pipe grid style super-shooter TED (Figure 7), one of the commonly used TEDs in the OGSF. The experimental trawl was equipped with the TTED (Figure 8). Though the webbing in which the TTED and TED are mounted may be of different brands, many configuration characteristics of the TTED and TED were comparable including: construction (aluminum), model (super-shooter), dimensions (approximately 129.5 cm high, by 107 cm wide), opening (double flap), chaffing gear, mesh size, and angle. The TTED and TED used in this study were set in the extension at 55° degrees of inclination relative to the water flow through the trawl, which is the maximum angle allowed by U.S. regulations. U.S. regulations also define the minimum inclination angle of the TED to be 35°. If the TED is set at less than 35° inclination, shrimp loss typically occurs; if the inclination is set higher than 55°, turtles may not be able to escape because the current could pin them against the four inch spaced bars, resulting in drowning. Even if the TED and TTED used in the experiment sometimes changed angle, all tows were included in the analysis regardless of angle, though angle may affect shrimp and bycatch retention. All comparisons used TEDs and TTEDs that were bottom opening, though the TTED and TED orientation of the escape opening (up or down) and the presence or absence of an accelerator funnel was dependent on the captain's preferred TED and TTED configuration. Only in GA did the captain prefer to not use funnels in the TED and TTED and in TX, MS and AL funnels were used.

All of the TTEDs were purchased new from Tide Marine Incorporated, in Bayou La Batre, AL. The TTEDs were bought pre-installed into stretch-resistant Sapphire webbing. Stretch-resistant webbing is believed to help prevent TEDs from losing optimal angle configuration so that less maintenance is required.. One difference between experimental and control tows was that the TTED weighed 27 kg when inserted in its tube of webbing with five hard floats, compared to the the four inch round bar TED and equivalent gear with only two hard floats which weighed about 20kg. Five hard floats were used with the TTED to ensure that it was positively buoyant in seawater. This did not make it noticeably harder to handle by crew.

Prior to beginning the comparative tows, it was necessary to determine if the trawl nets were fishing with the same efficency. If both experimental trawls were catching similar quantities of shrimp (less than 5% difference between both trawls) then the trawls were considered tuned. Therefore, I conducted standardization tows to compare catch rates between trawls. This also provided the captain with an opportunity to adjust the nets before the experiment began. Calibration of the trawls minimized, to the extent practicable, any trawl/side bias in catch prior to beginning a test series. Once the nets were 'tuned' and the experiment had begun, no changes or alterations to gear configuration and design were performed. If major changes were required, the test series was restarted following the change. Minor repairs to the gear (e.g., sewing holes in the webbing or replacing a broken tickler chain with a new one of the same configuration) were not considered a major gear alteration and the test series was continued. If a major gear change (i.e., changing nets, doors, or rigging) was required, the new trawl configuration would be re-tuned before a new test series began.

The primary assumption in assessing the shrimp catch and bycatch reduction efficiency of the TTED during these paired-trawl tests was that the experimental gear design (in this case the TTED) was the factor responsible for difference in catch from the control trawl equipped with a standard gear (in this case the TED). Consistent with past comparative towing experiments (Mitchell et al. 2002), I sought to further reduced potential side bias, resulting in differences in production from one side of the vessel to the other, by exchanging gear positions to collect data for an equal number of tows with the TTED and TED positioned in the outside port and starboard trawls. These changes occurred every two or three days so as to not hinder the vessel's shrimp production. Exchanging gear positions involved the removal of the TED extension still attached to its codend and the reinstallation of this gear in the outboard net located on the opposite side of the vessel.

Data collected during each tow included tow duration (hours), fishing depth (feet), vessel GPS position (start/stop locations), vessel speed (nautical miles along the ground), and gear operation observations (TED problems, non TED problems). The decisions on where (depth, location), when (day/night, duration) and at what speeds to trawl were at the captain's discretion. Fishing operations were interrupted only to maintain uniform fishing performance and to allow maintenance of the trawls. During these selectivity experiments, the captain performed tows that were typical of commercial fishing operations.

Tows that occurred with no apparent technical problems to the ship or trawl gear were considered "successful" and used in the final analyses. Data collected from tows with non-TED or TTED related problems were coded as unsuccessful and were not included in the analyses. Potential non-TED related problems included loose bag lines, obstruction of the trawl with large debris, fouled tickler chains, torn nets, twisted bags, and "mud tows". If it was apparent the TTED or TED caused a problem, (i.e. clogging of the TED or TTED by debris or animals) then the tow was recorded as 'TED clogged' and the data were used in the analysis.

Data were collected to compare catches of small finfish, large finfish, crustaceans, sharks, rays, and jellyfish from the TTED and TED trawls. Catches from the trawls were kept separate on the back deck using wooden structures that were adapted to fit the dimensions of each boat participating in the study. Following each tow, total catch weight and total shrimp weight were determined for the TTED and TED trawls. To calculate total catch weight after each tow the total number of standard baskets of bycatch from the TTED and TED trawls was determined and this number was multiplied this by the weight of one randomly selected basket from each respective trawl. If the catch was deemed too large to be measured (>14 baskets) the total number of baskets was estimated, and recorded as an "estimate" and therefore could not be used in bycatch reduction analysis.

To obtain a total shrimp weight from each TTED and TED trawl, crewmembers and the researcher removed all shrimp from the catch, which was then weighed. Select bycatch species such as Red Snapper and all sharks were individually measured and weighed for the entire catch from TTED and TED trawls. When possible, these species were released alive and venting of the red snapper swim bladder was conducted to increase the chance of survival of these fish.

To evaluate the species composition of the total catch from each TTED and TED trawl, a subsample of one basket (approximately 32 kg) was sorted into predetermined taxonomic categories (species, family, etc). Shrimp were separated from the subsample, individuals were counted and the total was weighed to determine average shrimp size. In accordance with the NMFS observer protocol, non-penaeid crustaceans (crustaceans), non-crustacean invertebrates and debris (rocks, logs, trash, dead seashells, sea grass) were grouped and weighed. The weights and counts of fish species of commercial, recreational and/or ecological importance were also recorded from the subsamples individually. These included: Atlantic Croaker, Black Drum, Cobia, King Mackerel, Lane Snapper, Longspine Porgy, Red Drum, Sea Trout, other snapper (other than Red Snapper), Southern Flounder, Spotted Sea Trout, Spanish Mackerel, Vermilion Snapper, and Gulf Flounder. Gulf Flounder and King Mackerel found in the subsample were individually weighed and measured. The remaining finfish species from the subsample were grouped into the "other" finfish category (Scott-Denton et al. 2012).

A concern with the NMFS observer protocol raised in the literature has been the lack of randomness of sub-samples. Based on the NMFS observer protocol, observers are required to mix the catch with a shovel to ensure a random sample, but this is sometimes difficult to do because of the weight of the catch, the position of the culling tray, the size of the boat and/or weather conditions (Diamond 2004). In addition, some species such as crabs may redistribute themselves after the catch is mixed by simply walking away, making it difficult to get a truly random sample. Nonetheless, I attempted to collect a random sample as soon as the catch was culled on the back deck to reduce the amount of time that the crabs had to escape the catch.

Due to the low abundance of sharks relative to other finfish species captured in trawls, ensuring that shark species are adequately accounted for in a subsample may be difficult (Belcher et al. 2010). To address this issue I collected information from all sharks captured in both the TTED and TED trawls. In comparison with data collection in 2012, where I sometimes recorded grouped weights of sharks in an attempt to release as many as possible alive, in 2013, I measured the length of each individual shark encountered, a practice that likely increased shark mortality. If there was any uncertainty regarding the species identity of a shark, pictures of the individual's mouth, head (top, bottom and profile) were taken so that a specialist could be consulted to confirm species identity.

Statistical Analysis

Catch data from the paired tows were used to estimate the efficiency of the TTED relative to the TED. Data from the TED and TTED-equipped trawls were analyzed to determine if there was a difference in the retention of particular species or species grouping (groups). Two approaches were used to analyze the data from this study. The first one is commonly used by the National Marine Fisheries Service scientists and consists of comparing CPUEs of experimental and control gears for individual species or group weights for every tow in the data set. Additionally, a CPUE analysis on numbers of individuals was conducted. Paired *t*-tests of CPUEs based on numbers and weights of animals were used to determine if differences were significant. To run the *t*-test I used the PROC TTEST procedure in SAS/STAT® v 9.2 software. To satisfy the assumptions of the statistical test, the data were tested for normality with SAS/STAT® PROC UNIVARIATE. In addition to the paired *t*-test approach, a generalized linear mixed model (GLMM) was constructed to evaluate the differences in relative efficiency of the TED compared to the TTED for species and groups (Holst et al. 2009).

Fishing operations in Georgia (GA), Texas (TX), and Mississippi (MS) varied by vessel size, trawl design, trawl area, fishing time, catch composition, TED design, etc., and this prevented pooling of the data from these regions. Therefore modeling of CPUE and General Linear Mixed Models (GLMM) analyses were conducted on an area by area basis. For GLMMs the analytical approach was based on the method described in Cadigan et al. 2006. I assumed that the differences in the designs of the TED and TTED were the only two differences between the trawls for each cruise. The hypothesis tested posits that both gears have a unique catchability (q) where q_r represents the q of the TTED and q_f represents the q of the TED. The efficiency of the TTED relative to the TED is equivalent to the ratio of the two qs:

$$\rho_l = \frac{q_r}{q_f} \tag{1}$$

The q of each gear was not measured directly, but the random effects model accounts for the differences in animal density encountered by both gears and therefore the differences in observed catches, for all trips, reflected the difference in qs of the TED and TTED.

C_{iv} represent the species or grouping catch at station i by gear v, where $v=r$ denotes TTED and $v=f$ denotes TED. λ_{ir} represent the species or grouping density for the i^{th} station by the TTED and λ_{if} represents the densities encountered by the TED. I treated station as a random variable since I assumed that animal volume and gear performance, at tow i, are subject to variations in animal patch size (i.e. abundance) and coverage (i.e. door spread) during a paired tow. The probability that an animal was captured during a tow is given as q_r and q_f. These probabilities may differ for each vessel, but are expected to be constant across stations. Assuming that capture follows a Poisson distribution where the mean is equal to variance, then the TTED and TED catch is given by:

$$E(C_{if}) = q_f \lambda_{if} = \mu_i \tag{2}$$

and:

$$E(C_{ir}) = q_r \lambda_{ir} = \rho \mu_i \exp(\delta_i) \tag{3}$$

where δ_i =log ($\lambda_{ir}/\lambda_{if}$) and λ is the animal density (count). For each station, if the standardized density of animals encountered was the same for the TED and TTED then δ_i=0. If the TED and TTED encountered the same animal density for a given tow (i.e. $\lambda_{ir}= \lambda_{if}$), then ρ can be estimated via a Poisson generalized linear model (GLM). The GLM approach is complicated because n can be very large if many tow stations and length classes are sampled (i.e. n > 1000), which means that there are many μ parameters to estimate. This also complicates constructing confidence intervals for ρ (Cadigan et al. 2006). Though this was not the case for my data (no single species with n>1000), I chose to use the conditional distribution of the catch by the TTED at station i, given the total non-zero catch of both gears at that station. c_i represents the observed value of the total catch. The conditional distribution of C_{ir} given C_i=c_i is binomial with:

$$\Pr\left(C_{ic} = x \middle| C_i = c_i\right) = \left(\frac{c_i}{x}\right) p^x (1-p)^{r_i - x} \tag{4}$$

where $p=\rho/(1+\rho)$ is the probability that an animal is captured by the TTED. In this approach, the only unknown parameter is ρ and the requirement to estimate μ for each station is eliminated, which is a condition otherwise required by the GLM approach (equations 2 & 3). For the binomial distribution, $E(C_{ir})=c_i p$ and $Var(C_i r)=c_i p/(1-p)$, therefore:

$$\log\left(\frac{p}{1-p}\right) = \log(\rho) = \beta \tag{5}$$

However, the model in equation 5, does not account for spatial heterogeneity in animal densities encountered by the TED and TTED for a given tow. If such heterogeneity does exist then the model becomes:

$$\log\left(\frac{p}{1-p}\right)=\beta+\delta_i \tag{6}$$

where δ_i is a random effect assumed to be normally distributed with a mean=0 and variance=σ^2. This model is used to estimate the gear effect $exp(\beta_0)$ when catch per tow is pooled over lengths.

In general, TEDs and selective grids are engineered to exclude (select) animals based on their size, of which length is a proxy. For this study, due to the differences in bar spacing, the expectation is that the TED will capture animals at different lengths (l) than the TTED. Models that account for length effects are extensions of the models described previously, which are used to define the relative efficiency of the total number of animals captured per tow. Again, assuming differences in standardized animal density exist between tows, a binomial logistic regression GLMM for a range of length groups would be:

$$\log\left(\frac{p_i}{1-p_i}\right)=\beta_0+\delta_i+\beta_1 l,\delta_i\sim N(0,\sigma^2),i=1,\ldots,n. \tag{7}$$

For this model, the intercept (β_0) can vary randomly with each station.

Adjustments for sub-sampling of the catch

Due to large catch volume, all tows were subsampled and model adjustments were required to account for this. Analysis must account for subsampling to ensure that common units of effort are compared. Let q_{ir} equal the sub-sampling fraction of the catch at station i for the r (TTED). This adjustment results in a modification to the logistic regression model defined as an offset in logistic regression to give a statistical frame of reference:

$$\log\left(\frac{p_i}{1+p_i}\right) = \beta_0 + \delta_i + (\beta_1 * l_i) + \log\left(\frac{q_{ir}}{q_{if}}\right), \delta_{ij} \sim N(0, \sigma_j^2), i = 1,\ldots,n. \qquad (9)$$

My analysis of the efficiency of the TED relative to the TTED consisted of multiple levels of examination. For animals with length measurements the full model consisted of unpooled (by length) catch data. Model fit was assessed by Akaike's Information Criterion (AIC). If AIC and factor significance indicated that length was not significant in predicting relative efficiency, shark, hammerheads and Red snapper data were pooled over length. For all other species, the full model consisted of pooled (numbers of individuals) catch data. The random intercept model was evaluated for all species and species groups to assess the relative differences in total catch of individuals (see equation 6). I then determined percent difference in relative efficiency based on the results of the intercept estimate at the mean value for the variables determined to be significant predictors of relative efficiency. To fit the GLMM I used the SAS/STAT® PROC GLIMMIX routine.

I used General Linear Models (GLMs) when the GLMM did not converge to yield parameter estimates to evaluate the shrimp and some rare species catch efficiency in the TTED relative to the TED-equipped trawl. To create this GLM I simply reduced the GLMM described above by removing the random effect. To fit a GLM, I used the SAS/STAT® PROC MIXED routine of the v. 9.2 software.

Before running GLMM or GLM, I conducted a correlation analysis on all variable for all cruises to insure that my variables where independent from one another (Table 1) using the SAS/STAT® PROC CORR routine.

CHAPTER 3: 2012 GEAR COMPARISONS

Introduction

Bycatch of turtles and finfish is a serious problem in the shrimping industry. The use of turtle exclusion devices (TED) in shrimp trawls has greatly reduced sea turtles bycatch; however, their effectiveness in excluding fishfish bycatch has not been successful (GMFMC 2007). The trash and turtle excluder device (TTED) is a new approach to decrease finfish bycatch on shrimp vessels. The TTED differs from the TED in that it has five centimeters of spacing between the bars of the grid rather than the 10.2 centimeters of spacing between the bars of the TED. The objective of this research was to compare the capture efficiency of the TTED-equipped trawl relative to the TED-equipped trawl in reducing bycatch and maintaining shrimp catch.

Comparisons of the TTED and TED were conducted in the summer of 2012 on three cruises in the offshore shrimp fishery of the South Atlantic Bight and Gulf of Mexico. This chapter describes the results of those comparisons including the number of days at sea, tow times, tow depths, number and weight of each species or species group caught for each cruise. Fork length measurements were obtained for sharks (all species) and Red Snapper, two groups with important management implications associated with their bycatch by the offshore shrimp fishery.

Catch per unit effort (CPUE) was estimated for each tow, both by weight and numbers of individuals. The *t*-tests were conducted on these data as described in Chapter 2 to compare CPUEs of the TTED and TED for all three cruises. Models were developed to provide insight into factors influential in describing the observed trends in the relative capture efficiency of species and species groups between the TTED and TED equipped trawls.

Materials and Methods

Captains of shrimp fishing vessels in Georgia (GA), Mississippi (MS), Louisiana (LA) and Texas (TX) were offered the opportunity to participate in this TTED study. One GA captain was willing to volunteer his time and vessel for the study. With the help of the Gulf and South Atlantic Fisheries Foundation (GSFF) and the NOAA Southeast Fisheries Science Center's (SEFSC) Pascagoula Lab, two more captains, one from TX and on from MS, volunteered to participate. Cruise dates were then coordinated.

During the 2012 field season, the NMFS shrimp observer protocol was followed (see Chapter 2). However, a few procedures were modified to accommodate the short time intervals between tows on the GA cruise. For example, when a large number of Atlantic Sharpnose Sharks were caught during the GA cruise, individuals of similar sizes were placed into baskets and weighed. Sharks were then counted for each size category and immediately released overboard. Since the TTED-equipped trawl did not catch many adult sharks relative to the TED-equipped trawl, sampling of sharks started with adults on the TED side and then moved on to the TTED-equipped trawl side. Weights of individuals were estimated by dividing the basket weight by the number of individual Atlantic Sharpnose Sharks in the basket. This sampling procedure prevented exposing the sharks to air for extended periods of time, and most were released alive. When sharks were less abundant, all individuals were measured.

A length-weight conversion was used to estimate lengths of all individual Atlantic Sharpnose Sharks that were not measured individually. The length-weight relationship is presented in the 2013 coastal shark stock assessment (SEDAR 34):

$$\text{Fork length (cm)}=\exp\left(\left(\ln(\text{weight (kg)}/\ 5.56 * 10^{-6})\right)/3.074\right)$$

This conversion was only conducted for the GA cruise, when shark lengths were not directly measured to minimize shark mortality during sampling.

During the MS cruise, sea robins *Triglidae* spp., lizardfishes *Synodontidae* spp., and larger crabs (Rooster Crab *Calappa flammea* and blue crabs *Callinectes spp.*) were separated into large and small size categories within each group to better quantify observed differences in the capture of these species groups between the TTED-equipped trawl and the TED-equipped trawl. Large sea robins were defined as weighing more than 0.175 kg, large lizardfishes were defined as weighing more than 300 g, and large crabs (unclassified) were defined as weighing more than 200 g. These designations were made based on my observation that large individuals were less frequent, but not absent, in the TTED-equipped trawl catch. Large individuals were counted and weighed, while small individuals were only weighed. Separating sea robins, lizardfishes and crabs into large and small size categories was only conducted on the MS cruise.

The comparative towing studies were completed during three cruises over the course of 71 days. The GA, TX and MS cruises lasted 13, 32, and 27 days at sea, respectively (Table 2). All three vessels were steel-hulled, and each had a different length, engine power and make, headrope length, trawl shape, and door type. Door type is an important factor since the hydrodynamic effects from the doors spread open the trawl. When water is accelerated around the backside of the doors, it creates a negative pressure, generating lift, or a spreading force in the case of trawl doors. The doors used on the TX cruise were cambered, vented, oval in shape, and were much shorter horizontally and taller vertically than the wood and aluminum doors from the GA and MS cruises, respectively. The doors from the GA and MS cruises were flat, rectangular boards. Other components of the shrimp trawl gear that were measured in this study, such as trawl shape, bridle length, and cable are summarized in Table 3. The technical differences between these vessels reflect but are not fully representative of the heterogeneity of the shrimp-fishing fleet.

Initially, *t*-tests on CPUE were conducted by cruise for each group of bycatch species to determine whether catch differences between TTED-equipped trawls and TED-equipped trawls were significant. General linear mixed models (GLMM) and general linear models (GLM) were used to calculate differences in catch efficiency and also to determine those parameters which best predicted catch efficiencies.

Results

On the GA cruise, fishing occurred off the coasts of South Carolina and Georgia (Figure 9). On the TX cruise, fishing began offshore of Cameron, LA, and then moved into TX offshore waters for the opening of the shrimping season on July 15th. For the MS cruise, fishing occurred from the MS state line south to the mouth of the Mississippi River in Louisiana. For the GA, TX, and MS cruises, there were 35, 71, and 43 comparative tows of which 31, 44 and 35 were valid (as defined in Chapter 2), respectively. Valid tows from each cruise were partitioned so that the TTED was installed in the port and the starboard nets almost equally. Tow characteristics, including tow depth, tow times, and time of fishing, are summarized in Table 4.

CPUE Total Catch - The total catch weights (target catch and all bycatch) of the TTED-equipped trawl and the TED-equipped trawl on the GA cruise were 3,159 kg and 5,201 kg, respectively (Table 5). The total catch weight for the TTED-equipped trawl and the TED-equipped trawl on the TX cruise were 10,584 kg and 10,716 kg, respectively. The total catch weight for the TTED-equipped trawl and TED-equipped trawl on the MS cruise were 7,657 kg and 8,238 kg, respectively. The total catch reduction of the TTED-equipped trawl relative to TED-equipped trawl was 39.27%, 1.27% and 7.05% for GA, TX, and MS, respectively. CPUE calculations and *t*-tests were not conducted on total catch weight.

CPUE for shrimp – The TTED-equipped trawl significantly affected shrimp weight CPUE during both the GA and TX cruises relative to the TED-equipped trawl. However, the TTED had opposite effects on the two cruises, significantly decreasing CPUE on the GA cruise, significantly increasing the CPUE on the TX cruise, and having no significant effect on the MS cruise. The total White Shrimp weights for the TTED-equipped trawl and the TED-equipped trawl on the GA cruise were 824 kg and 856 kg, respectively (Table 6). Weight CPUE for White Shrimp on the GA cruise was significantly reduced by 4.32% (p = 0.04885) in the TTED-equipped trawl relative to the TED-equipped trawl (Table 7). The total Brown Shrimp weights for the TTED-equipped trawl and the TED-equipped trawl on the TX cruise were 3,058 kg and 2,895 kg, respectively. Weight CPUE for Brown Shrimp on the TX cruise was significantly increased by 6.07% (p = 0.01106) in the TTED-equipped trawl relative to TED-equipped trawl. The total Brown Shrimp weights for the TTED-equipped trawl and the TED-equipped trawl on the MS cruise were 1,633 kg and 1,653 kg, respectively. Weight CPUE for Brown Shrimp on the MS cruise was reduced by 1.58% in the TTED-equipped trawl relative to the TED-equipped trawl, although this difference was not statistically significant.

CPUE for large fish - The catch weights and corresponding CPUEs for all fish species and species groups are presented by cruise in Table 8, Table 9 and Table 10, for GA, MS, and TX, respectively. Numbers of individuals and the corresponding CPUEs for all fish species and species groups are presented by cruise in Table 11, Table 12, and Table 13, for GA, MS, and TX, respectively. *T*-test results of weight CPUEs (Table 14, Table 15, Table 16) and number CPUEs (Table 17, Table 18, Table 19) of all species and species groups are presented by cruise. For each cruise I report on those species and groups with significant CPUE differences between the TTED-equipped trawl and TED-equipped trawl. I also report on all shark species and Red Snapper regardless of significance in difference of CPUE in the TTED-equipped trawl relative to the TED-equipped trawl.

GA Large Elasmobranchs CPUE - Weight CPUEs for adult Atlantic Sharpnose Sharks, neonate Atlantic Sharpnose Sharks, Bonnethead Sharks, Blacknose Sharks, rays and skates group were reduced by 99.9% (p <0.0001), 41.1% (p = 0.0206), 99.3% (p = 0.0103) and 93.4% (p <0.0001) in the TTED-equipped trawl relative to the TED-equipped trawl, respectively. Weight CPUEs of Blacktip Shark, Smooth Hammerhead, Scalloped Hammerhead, Spanish Mackerel, and Southern Flounder were reduced by 100%, 96%, 91.1%, 74.3% and 100%, in the TTED-equipped trawl relative to the TED-equipped trawl, respectively. These reductions were not statistically significant due to low frequency of occurrence of these animals. In comparison with weight CPUE, the number CPUE indicated a reduction of 100% for Blacktip Sharks in the TTED-equipped trawl relative to the TED-equipped trawl, and this difference was statistically significant (p = 0.0026).

TX Large Fish and Elasmobranches – For the TX cruise, the weight CPUE for adult Atlantic Sharpnose Sharks was reduced by 93.4% (p = 0.0009) in the TTED-equipped trawl relative to the TED-equipped trawl. The weight CPUEs of Dusky Shark, Blacknose Shark, Southern Flounder, Atlantic Angel Shark, and the rays and skates group were reduced in the TTED-equipped trawl relative to the TED-equipped trawl by 100%, 100%, 100%, 85.7%, and 76.5%, , respectively. These reductions were not statistically significant. In comparison with weight CPUE, the number CPUE indicated a reduction of 100% for Southern Flounder in the TTED-equipped trawl relative to the TED-equipped trawl, and this was significant (p = 0.0492). Catches of Gulf Smoothhound were reduced by 32.2% in weight and 28.24% in number in the TTED-equipped trawl relative to the TED-equipped trawl. These reductions were not statistically significant. Four large Red

Snapper measuring 67cm, 70cm, 73.5cm, 74cm and 88.3cm were caught on this cruise, all by the TED-equipped trawl.

MS Large Fish and Elasmobranchs - Weight CPUEs for large sea robins, Southern Flounder, rays and skates group, large lizardfishes, and Red Snapper were reduced in the TTED-equipped trawl relative to the TED-equipped trawl by 86.6% ($p = 0.0001$), 91.1% ($p = 0.0051$), 86.8% ($p = 0.0055$), 100% ($p = 0.0057$), and 61.3% ($p = 0.0383$), respectively. Catch weight CPUEs for Spanish Mackerel, Louisiana Redfish, and Gulf Smoothhound were reduced in the TTED-equipped trawl relative to the TED-equipped trawl by 100%, 100% and 95.2%, ,respectively. These reductions were not statistically significant. In comparison with weight CPUE, the number CPUE indicated a reduction of 85.26% for Gulf Smoothounds in the TTED-equipped trawl relative to the TED-equipped trawl, and this difference was significant ($p = 0.0144$).

*CPUE small fis*h - In comparison with large fish, only a few small fish species on any cruise exhibited significantly different weight CPUEs between the TTED-equipped and TED-equipped trawls. Weight CPUEs for lizardfishes on the TX cruise and Spot on the MS cruise showed increases of 26.3% ($p = 0.0459$) and 38.6% ($p = 0.0304$) in the TTED-equipped trawl relative to the TED-equipped trawls respectively. Weight CPUEs for combined small fishes are presented for each cruise in Table 20. Weight CPUE for small fishes on the GA cruise was reduced by 37% ($p < 0.0001$) in the TTED-equipped trawl relative to the TED-equipped trawl (Table 21). For the TX and MS cruises, weight CPUEs for small fishes were reduced in the TTED-equipped trawl relative to the TED-equipped trawl by 5.8% and 2.9%, respectively, but these reductions were not statistically significant.

CPUE crustaceans - On the GA cruise, weight CPUE for Horseshoe Crabs was reduced by 100% ($p < 0.0001$) in the TTED-equipped trawl relative to the TED-equipped trawl. On the TX cruise, weight CPUE for crustaceans (grouped) was reduced by 20.4% (p = 0.0012) in the TTED-equipped trawl relative to the TED-equipped trawl. On the MS cruise, weight CPUE of large crabs was reduced by 89.6% (p = 0.0008) in the TTED-equipped trawl relative to the TED-equipped trawl. Additional analyses using General Linear Mixed Models (GLMM) further supported these findings. In some cases the GLMM helped identify additional variables that were significant predictors of the capture efficiency of certain species and species groups in the TTED-equipped trawl relative to the TED-equipped trawl.

Generalized Linear Mixed Models - Generalized Linear Mixed Models (GLMM) were used to evaluate the capture efficiency of the TTED-equipped trawl relative to the TED-equipped trawl for different species and species groups. The variables evaluated by the model for the different species and species groups are described in Chapter 2. The choice of the best-fit model was determined by AIC. Table 22 summarizes the best model fit for the sharks and Red Snapper length measurement (unpooled) data. When length was not identified as a significant factor in the best-fit model for a species or species group, count (pooled) data were used to determine the best-fit model (Table 23). Only the cruise/species combinations with significant catch differences in the TTED-equipped trawl relative to the TED-equipped trawl are shown graphically. Graphical representations of the observed catches, for pooled or unpooled data, were based on the best-fit model. Model outputs provided estimates of the capture efficiency in the TTED-equipped trawl relative to the TED-equipped trawl. For shark species, graphical representations of catch in the TTED-equipped trawl relative to the TED-equipped trawl, even when the differences in catch were not statistically significant, are shown in Figures 16 and 17.

For Atlantic Sharpnose Sharks on the GA cruise, and grouped carcharhinids (grouped for all cruises), the best-fit model indicated that length was a significant predictor of the capture efficiency of the TTED-equipped trawl relative to the TED-equipped trawl (Table 24). For other shark species or species groups with length measurements, there were not enough data and/or frequent zero observations that prevented the model from converging. Parameter estimates from the length-based model for grouped carcharhinids was used to graph the differences in the capture efficiency in the TTED-equipped trawl relative to the TED-equipped trawl for captures of carcharhinids of various length (Figure 10). As illustrated in the graph, the TTED-equipped trawl captured fewer carcharhinids of all size categories than the TED-equipped trawl. The graph also indicated that the TTED excluded all carcharhinids above 65 cm in length whereas the TED-equipped trawl captured individuals up to one meter long. Though length was not a predictor of the capture efficiency for Gulf Smoothhound, the data show a general trend of fewer individuals captured for all sizes in the TTED-equipped trawl relative to the TED-equipped trawl (Figure 11).

Small fish bycatch - The pooled model (number of individuals) for lizardfishes of the TX cruise indicated a significant decrease of catch in the TTED-equipped trawl relative to the TED-equipped trawl (Table 25). The lizardfishes model for the TX cruise also indicates that tow depth was a predictor for the capture of the lizardfishes by the TTED-equipped trawl relative to the TED-equipped trawl. Figure 12 shows, the model results for lizardfishes of the TX cruise. The intercept model without variables is the best-fit model for large sea robins of the MS cruise, sea trouts of the TX cruise, and large crabs of the MS cruise (Table 26). This model indicates that there was a significant decrease in catches of large sea robins of the MS cruise, sea trouts of the TX cruise, and large crabs on the MS cruise in the TTED-equipped trawl relative to the TED-equipped trawl. Figure 13 shows catch data for large seas robins on the MS cruise, sea trouts on the TX cruise (Figure 14), and large crabs (rooster and blue crab) (Figure 15) on the MS cruise for the TTED-equipped trawl relative to the TED-equipped trawl. The majority of the models that used count data (pooled) (Table 26) indicate a reduction in catch efficiency, although not statistically significant, for small fish species in the TTED-equipped trawl relative to the TED-equipped trawl. Many models for species and groups analyzed in the GLMM framework could not calculate parameter estimates of relative efficiency as they failed to converge. This occurred because small numbers of paired tows and/or frequent zero observations for these infrequently encountered species or species groups did not provide enough data for the more complex GLMM. I therefore removed the random variables of the full GLMM, transforming it into a general linear model (GLM) capable of analyzing data from these 'rarer' species.

General Linear Model - The GLMs for comparing the capture efficiencies of the infrequently encountered species in the TTED-equipped trawl relative to the TED-equipped trawl were generally able to return parameter estimates of relative efficiency (the models converged) (Table 27). Catches of Atlantic Sharpnose Sharks on the TX and MS cruises (Figure 16), Bonnethead Sharks on the GA cruise (Figure 17), rays and skates group on the GA and MS cruises (Figure 18), Blackear Bass *Serranus atrobranchus* on the TX cruise (Figure 19), Vermillion Snapper *Rhomboplites aurorubens* on the TX cruise (Figure 20), and whitings *Merluccius spp.* on the GA cruise (Figure 21) all showed significant reductions in capture efficiency in the TTED-equipped trawl relative to the TED-equipped trawl. All other species modeled using the GLM had negative signs for the intercept parameter estimates, which indicated a reduction, although not statistically significant, in the capture efficiency of the TTED-equipped trawl relative to the TED-equipped trawl for small fish species (Figure 22). Only Red Porgy *Pagrus sedecim* on the TX cruise had a positive parameter intercept, which indicated an increase, although not statistically significant, in the capture efficiency of the TTED-equipped trawl relative to the TED-equipped trawl (Table 27). GLMs for Blacknose Sharks, Dusky Sharks and Spot on the TX cruise did not converge, since these species were encountered only once during this cruise (Table 27).

Shrimp catch (weight) retention was directly measured for the TTED-equipped trawl and the TED-equipped trawl for every tow. Shrimp catch weights from the TTED-equipped trawl and

TED-equipped trawl on the GA, TX and MS cruises were compared using GLMs. The best-fitting model for shrimp catch on the GA cruise was the intercept model (Table 28). The best-fit model for Brown Shrimp for both the TX and MS cruises indicated that total bycatch reduction (kg) was a predictor for catch efficiency in the TTED-equipped trawl relative to the TED-equipped trawl (Figure 23). This indicates that total bycatch weight reduction and shrimp catch weight decreased when bycatch was reduced. Model results provided estimates for catch efficiency of the TTED-equipped trawl relative to the TED-equipped trawl. The catch of White Shrimp on the GA cruise was reduced by 3.77%, in the TTED-equipped trawl relative to the TED-equipped trawl, but this reduction was not statistically significant. The catch of Brown Shrimp on the TX cruise was increased by 5.3% ($p = 0.0277$) in the TTED-equipped trawl relative to the TED-equipped trawl. The catch of Brown Shrimp on MS cruise was reduced by 1.26% in the TTED-equipped trawl relative to the TED-equipped trawl, but this reduction was not statistically significant.

Discussion

The 2012 sampling season provided an opportunity to compare shrimp retention and bycatch reduction between TTED-equipped trawls and TED-equipped trawls. The results of these experiments clearly indicate that size is a factor in determining which animals will be captured or excluded by the TTED-equipped trawl. The TTED captured fewer elasmobranchs than the TED-equipped trawl for all size classes encountered during the cruises, while catches of small animals, such as shrimp and small fishes, were not drastically reduced in the TTED-equipped trawl relative to the TED-equipped trawl. Analytical modeling techniques suggest that bycatch reduction is a significant predictor of TTED shrimp retention efficiency: when more bycatch is evacuated by the TTED or the TED, shrimp catch is also reduced by the TTED or TED respectively. Modeling results indicating substantial small fish bycatch reduction efficiencies and the results indicating that carcharhinids and lizardfishes catches on the TX cruise were affected by tow depth, require further attention.

Maintaining target catch rates is essential to the shrimp industry and will ultimately determine the acceptance of innovative fishing gears. Commercial shrimp boats participating in this study were not compensated, and there was an understanding that if shrimp losses were caused by the TTED, then use of the experimental gear would cease. In Georgia, I did not experience shrimp loss for the first nine tows. However, consistent shrimp losses by the TTED-equipped trawl were observed between tows 9 - 22. When hauling tow 21, the angle of the TTED was observed to have decreased. Unfortunately, the duration for which the TTED angle was altered is not known and while the angle of inclination of the TTED after tow 21 was not measured, the captain estimated it at well below 45°. This observed change of angle may have been caused by meshes stretching or because the grid was not properly secured in the webbing. After readjustment of the TTED angle, which was executed under less than ideal conditions (a moving sea with no angle measurement), shrimp loss was no longer observed for tows 22 - 32. Upon returning to port, the TTED angle was measured to be 60°, or 5° more than the mandated maximum angle of 55°. TTED angle was maintained at 55°-50° throughout the TX and MS cruises and both CPUE and GLMs did not indicate shrimp loss by the TTED-equipped trawl relative to the TED-equipped trawl. Interestingly, GLM models for TX and MS shrimp weight data indicated that total bycatch weight reduction was a predictor of the shrimp capture efficiency of the TTED-equipped trawls relative to the TED-equipped trawl. Based on models for TX and MS, I expected that total bycatch weight reduction would also be a predictor of the shrimp capture efficiency of the TTED-equipped trawl relative to the TED-equipped trawl for the GA cruise, since shrimp loss occurred and bycatch was reduced by 37%. However, the shrimp model for the GA cruise did not identify total bycatch reduction as a predictor of catch efficiency as there was little contrast between bycatch reduction and shrimp catch data. Indeed, total bycatch weight reduction in the TTED-equipped trawl relative to the TED-equipped trawl occurred for every tow regardless of shrimp loss or gain, which may explain the GA model results. The GA cruise shrimp weight CPUE *t*-test indicated significant shrimp loss of 3.7% by the TTED-equipped trawl relative to the TED-equipped trawl but, as noted above, some tows from this cruise may have been impacted by the TTED-equipped trawls reduced angle.

Examining the parameter estimates from the pooled GLM as well as the scatter plots of shrimp catches, it is clear that the catch efficiency of shrimp in the TTED-equipped trawl relative to the TED-equipped trawl was not reduced. Based on a combination of results from the three cruises in which the TX cruise had a significant gain of shrimp and the MS cruise had a non-significant loss, the null hypothesis that the TTED shrimp retention is not different from the shrimp retention of a TED, cannot be rejected. To this I add the caveat that results may be dependent on the inclination angle of the TTED since this seems to be a factor that alters the shrimp capture efficiency in the TTED-equipped trawl relative to the TED-equipped trawl.

Shark Bycatch - Shark data from the GA cruise included the majority of the observations for shark species in the entire study. The TTED was effective in reducing the capture of large quantities of Atlantic Sharpnose Sharks on the GA cruise. Length-weight conversion factors were used to estimate lengths of all individual Atlantic Sharpnose Sharks that were not individually measured on the GA cruise. Carcharhinid sharks were grouped across cruises to plot relative efficiency of TTED-equipped trawls and TED-equipped trawls as a function of length for as many individuals and lengths as possible. Triakiad sharks (smoothhounds) were excluded from the carcharhinid group based on difference in body shape: Carcharhinids are characterized as having flattened bodies with extended heads, while triakiads have slender bodies and nonlaterally expanded heads (Castro 2011). Driven primarily by the reduction of large fish by the TTED-equipped trawl, the null hypothesis that the fish bycatch retention of the TTED is not different from the fish bycatch retention of the TED was rejected. The alternative hypothesis, that the fish bycatch retention of the TTED is less than the fish bycatch retention of the TED was supported by the data.

Small Fish - For the GA cruise, *t*-tests of CPUEs of grouped small fishes indicated significant reductions in capture efficiency of the TTED-equipped trawl relative to the TED-equipped trawl. For the TX and MS cruises, the small fishes group included all the small fishes except for Red Snapper, while on the GA cruise this group included both small fishes and Cannonball Jellyfish *Stomolophus meleagris*, which sometimes contributed over half the weight of TED-equipped trawl catches. For the GA cruise, the subsampling procedures described in Chapter 2 were not completed and the small fishes weight in the GA cruise included jellyfish. I therefore suggest a cautious interpretation of the significance in reduction of small fishes bycatch on the GA cruise and propose that other factors may have contributed to the observed difference in small fishes for this cruise. These factors include escapement of small fishes during large fish bycatch exclusion, small fishes escaping with low TTED angle, and finally, the active use of BRDs in both cod-ends. Small fish might have escaped more from the TTED-equipped trawl relative to the TED-equipped trawl because the TTED's flap was probably more affected by evacuated large animals (i.e., jellyfish, sharks and horseshoe crabs). The TED side caught many more large animals than the TTED-equipped trawl side. This indicates that the TTED-equipped trawl evacuated large animals and therefore the flap was likely opened more frequently, permitting the escape of small fishes from the TTED-equipped trawl more frequently than the TED-equipped trawl. In addition to the effect of large animal bycatch reduction on small fishes bycatch, the TTED's reduced angle may have contributed to high levels of bycatch reduction observed on the GA cruise.

Another factor that may have contributed to observed small fishes bycatch reduction was the active use of BRDs on the GA cruise since a Letter of Authorization (LOA) from NOAA SEFSC to deactivate mandatory BRDs for the trip was not procured. Fisheye BRDs used during the GA cruise may have confounded the effects of bycatch reduction of small fishes in the TTED-equipped trawl relative to the TED-equipped trawl. Both fisheye BRDs were identical in dimensions, located top central position, behind the TED extension and directly in front of the chafing gear of the cod-end. Given that the BRDs were identical for both trawls, their effect on small fishes bycatch may have been similar. However, it is also possible that the reduced catch of large animals by the TTED on the GA cruise may have improved the efficiency of the fisheye to reduce bycatch of small fishes in the TTED-equipped trawl relative to the TED-equipped trawl. If, for example, the catch reaching the codend was 'cleaner' (i.e. fewer large animals) in the TTED-equipped trawl relative to the TED-equipped trawl, then the small fishes may have had a better opportunity to school and orient themselves towards the fisheye and escape. Again, the many variables that were part the GA experiments do not allow for a meaningful conclusions regarding small fishes bycatch when compared to the TX and MS cruises. In comparison with the TTED catch from the GA cruise, the TTED catches from the TX and MS cruises were not affected by reduced angle of the TTED or jellyfish. Driven primarily by lack of small fish bycatch reduction by the TTED in TX and MS, the null hypothesis that the fish bycatch retention of the TTED is not different from the fish bycatch retention of the TED was not rejected.

Intercept parameter estimates and resulting percent differences in the catches of lizardfishes from the TX cruise, Butterfish, from the TX and MS cruise, sea robins from the TX cruise, and Rock Seabass *Centropristis philadelphica,* from the TX cruise were reduced. In fact, the catches of these species or species groups were reduced by 100% in the TTED-equipped trawl relative to the TED-equipped trawl. These differences are indicative of subsampling bias and/or error since it is unlikely that small fish catch would be reduced by 100% in the TTED-equipped trawl relative to the TED-equipped trawl. The data for lizardfishes from the TX cruise indicated that there were tows that had high numbers of lizardfishes in one trawl and none in the other. This anomaly in data recording resulted from the subsampling procedure: When lizardfishes were not numerically dominant in a subsample they were included in the 'other fish' group. As an example, if in the TTED-equipped trawl subsample there were 20 lizardfishes and only 5 in the TED-equipped trawl, then the TTED would have a lizardfishes group with 20 fish and the TED-equipped trawl would have none since those lizardfishes would have been included in the 'other fish' group. This difference was further accentuated by the extrapolation of lizardfishes from the subsample to the total catch of lizardfishes. To examine this possibility, I ran one model on the lizardfishes catch data from the TX cruise in which all observations with lizardfishes catch in one trawl and zero catch in the other were removed. For the regrouped (small and large) lizardfishes on the TX cruise I removed data from tows 57, 65, 47, 26, 56, 40, 64, 59, 45, with 45, 45, 49, 51, 51, 61, 64, 79, 127 individuals caught in the TED-equipped trawl, respectively and zero caught in the TTED-equipped trawl. I also removed data from tows 30 and 32 with 159 and 49 lizardfishes individuals caught in the TTED-equipped trawl and zero caught in the TED-equipped trawl. The model was run on this revised data set and the result indicated a catch efficiency increase of 5.82% in the TTED-equipped trawl relative to the TED-equipped trawl. A 5.82% increase in lizardfishes by the TTED-equipped trawl relative to the TED-equipped trawl for the TX cruise is not only more reasonable than a 100% increase in lizardfishes but the fitted line representing catch efficiency of the TTED-equipped trawl relative to the TED-equipped trawl better described these data (Figure 24). This example illustrates that some species of small fishes, and in particular those that are not listed as species of interest in the NMFS observer protocol, may not have accurate count or weight data for every tow. Other species that were not considered as species of particular interest but were analyzed here include sea robins, Rock Seabass, Blackear Bass, Oscillated Flounder, and Red Porgy.

The GLMM model on grouped carcharhinids indicated that tow depth was a significant variable for predicting catch efficiency in the TTED-equipped trawl relative to the TED-equipped trawl. In this case however, sampling artifact is likely the reason tow depth was determined to be a significant predictor. Neonate Atlantic Sharpnose Sharks were captured on the GA cruise only, where tows occurred in much shallower waters than those sampled on the TX and MS cruises. Based on the GA cruise depth and neonate Atlantic Sharpnose shark catch, the model determined that tow depth was a factor in determining the capture efficiency of the TTED-equipped trawl and the TED-equipped trawl for grouped carcharhinids. For some larger fish species such as Blacknose, Blacktip, Smoothhounds, Scalloped Hammerhead and Bonnethead sharks, rays and skates, Southern Flounder, and Spanish Mackerel, the parameter estimates were high and resulted in high bycatch reduction estimates (30-100%) because there were only one to three individuals in the TTED-equipped trawl relative to the TED-equipped trawl, which had two to ten times as many animals (Table 29). In cases where there was only one individual captured by the TED-equipped trawl and none captured by the TTED-equipped trawl, such as for Blacknose and Dusky sharks on the TX cruise, the models did not converge.

Some of the differences in fishing and experimental procedures that occurred on the GA, TX and MS gear evaluations in 2012 were considered for the planning the 2013 field season. After having conducted my 2012 comparative towing study on the east coast and the GOM in 2012, I learned that the GOM may be better suited for collecting data in accordance with the NMFS observer protocol. Difficulties with the research protocol in the field were encountered predominantly during the GA cruise. In addition to the differences in sampling procedures conducted on the GA cruise, there were also major differences in fishing strategies between this cruise and the other 2012 GOM cruises. On the GA cruise, four to five tows were conducted per day, and in TX and MS, generally two tows per night were completed. Cruises in GA lasted a maximum of six days since the shrimp were preserved on ice, but the TX and MS vessels had freezing capacity onboard, allowing for cruises of 25-30 days.

On the GA cruises, calibration tows were not conducted and thus it was not possible to evaluate if the two trawls were fishing similarly before beginning the gear evaluations. Bias between paired tows (i.e. port versus starboard trawls) can be controlled by conducting the same number of tows with the TTED on both sides of the boat (Mitchell et al. 2002). Though it is acceptable to proceed with comparative towing evaluations without calibration tows, these can help to quickly identify if the experimental gear results in catch loss. Further, when calibration tows are performed and a trawl-side bias is observed, trawl gear can be adjusted before the comparisons begin. If comparisons begin after a trawl-side bias has been identified, the bias is expected to continue when experimental gear is tested. Thus when conducting evaluations with the TTED, the use of calibration tows are recommended.

For the reasons discussed above, it was not possible to fully adhere to research protocols on the GA cruise where shrimp trawl vessels operate under a rapid succession of day light tows, driven in part by the need to maximize shrimp production in trips of shorter duration. Based on discussions with captains and crew, it was suggested that I focus my 2013 field season in the GOM, specifically concentrating my effort in the fall when large fish are more abundant in the bycatch.

CHAPTER 4: 2013 GEAR COMPARISONS

Introduction

The summer 2012 gear comparisons (Chapter 3) in Georgia (GA), Texas (TX), and Mississippi (MS) demonstrated the potential of the trash and turtle excluder device (TTED) to reduce bycatch in the offshore shrimp trawl fishery. These comparisons provided critical insights for the planning of future TTED research, such as targeting areas and seasons with an abundance of large fish bycatch. As a result, the 2013 comparisons were focused on longer duration fishing trips in the Gulf of Mexico (GOM) during the fall season, which was chosen to increase the likelihood of interactions between the experimental gear and large fishes.

The 2013 sampling season was generally a success; however, due to an unfortunate incident, all of the data, photographs, and notes from the fall 2013 cruises were destroyed. A quantitative treatment of the results is thus not possible. Consequently, this chapter describes modifications that were made to the protocols during 2013 and presents a qualitative account of the results, including information on catches of fishes, invertebrate species, as well as targeted shrimp species.

The 2012 comparisons confirmed that the TTED-equipped trawl reduced the capture of carcharhinids relative to the TED-equipped trawl. As noted in Chapter 1, Red Snapper and Blacknose Shark bycatch reduction is of particular concern to the shrimping industry. Though we encountered many sharks during the comparisons in GA, we did not encounter many large bony fishes of any species during the 2012 GOM comparisons. During those cruises, some shrimp fishermen suggested that the ideal season for conducting a new series of comparisons with the TTED-equipped trawl would be during the fall, when catches tend to include greater numbers of large bony fishes. As a result, the 2013 comparisons were focused between mid-September and mid-December in the GOM.

Materials and Methods

I contacted captains of shrimp fishing vessels in Alabama (AL), Louisiana (LA), and MS to determine if their boats could provide an appropriate sampling platform and if they would be willing to participate in the research. I met with several captains and although interested in my research, none were willing to accept me on board without financial compensation. With the help of the Alabama Seafood Alliance, I was introduced to one captain who was willing to host my comparisons on his boat free of charge. We agreed that I would embark for one trip to test the TTED, with the stipulation that if shrimp losses were observed we would switch the experimental gear to a TED with a wider bar spacing of 2.25 in.

Once the captain felt that his gear was set such that the fishing configuration was optimal, I used calibration tows to determine if the trawls were fishing similarly. Based on the results of eight calibration tows, the captain and I both felt comfortable with starting the comparisons.

In addition to the subsampling protocol procedure described in Chapter 2, I elected to perform additional procedures that would allow more accurate quantification of catch characteristics. Adaptations to the sampling protocol were adopted for the crab, lobster and sponge bycatch categories. Large crabs in the subsample were separated from small individuals. Small individuals of different species were weighed together in the group "Crustaceans," whereas large individuals were separated by species, counted and weighed. For spiny lobsters, which were frequently captured in 2013, I recorded the total number of large individuals and their total weight from both trawls. Small lobsters from the subsample were included in the

Crustaceans group. Sponges, which were only encountered in 2013, were treated separately from the rest of the bycatch to ensure that the high volume-to-weight ratio did not affect extrapolations of total bycatch weight from the TED-equipped trawl. Separating all visible sponges from the total TED-equipped trawl catch and recording their weight separately from the rest of the bycatch accomplished this. I systematically photographed the fish bycatch baskets and sponge bycatch baskets from the TED-equipped trawl and TTED-equipped trawl to show the effect on catch volume caused by the capture of sponges. Any remaining sponge fragments in the subsample were separated from other debris in order to extrapolate the sponge fragment weight to the total bycatch weight. I was then able to add the total small catch weight of sponge fragments to the catch of large sponges to obtain an accurate measurement of total sponge bycatch from each experimental trawl.

Results

I spent a total of 55 days at sea during the fall 2013 sampling season, which extended from September 23 to December 7 (Table 30). During this period, an additional 29 days were lost due to two tropical storms, one main engine problem, one generator problem, one autopilot compass problem, the passing of a crew's family member, and the typical one week break between trips.

During the 55 days at sea, I completed eight comparative calibration tows in which the two trawls had a typical TED and 85 comparative tows between the TTED and the TED. Of the 85 tows comparing the TTED and TED, 67 tows were successful (i.e., tows that occurred with no apparent technical problems to the ship or trawl gear). Of the 67 successful tows, 20 tows targeted Brown Shrimp *Species*, 29 tows targeted Pink Shrimp *Species*, 10 tows targeted Royal Red Shrimp *Hymenoppenaeus robustus*, and 8 tows targeted White Shrimp.

The first trip was conducted in waters between the MS state line and Tiger Pass, LA, just west of the Mississippi River Channel. During this trip, we encountered incidental delays, which extended the trip until October 27 for a total of 35 days, of which only 21 days were actually spent at sea. I embarked for my second voyage on November 4 for a 36-day fishing trip. We traveled to fishing grounds located four days away, west of St. Petersburg FL, and steadily fished south towards Key West and the Dry Tortugas. We spent four days targeting Royal Red Shrimp in areas south of the Florida Keys, after which we resumed targeting Pink Shrimp. On December 2, we returned north after hearing reports of large White Shrimp catches closer to AL. We reached waters offshore of AL on December 5 and returned to port on December 9. On the morning of December 10, my vehicle was stolen and destroyed along with all of its contents. Though I do not have data for analysis, I do have a good recollection of what I observed at sea.

Research Protocol and Gear - During some tows, the inclination of the TTED changed from 55° to 45°. When the TTED was fishing at low angle of inclination, there was a reduction of shrimp catch and small fish bycatch. These losses occurred when the TTED grid reached an inclination of 45°. When the inclination of the TTED angle was increased to the original angle of 55°, the catches of shrimp and small fish bycatch were comparable to those from the TED. Though this occurred only twice during the 2012 and 2013 sampling seasons (121 days at sea), the results appeared to indicate an increased sensitivity of the TTED to inclinations at or below 45°. Unfortunately, I was not able to continue observations of reduced shrimp and small fish catches at reduced TTED angle since the boat was trying to maximize shrimp production and therefore needed to maintain optimal gear configuration. I also checked to confirm that the TED angle of inclination was set to 55° every time I moved the gear to the opposite trawl, to reduce catch rate bias. In one instance I observed a TTED from one of the experimental trawls warp into a concave shape (similar to a Pringles potato chip). This occurred when the catch from that trawl was composed predominantly of shells. These issues did not undermine the results of the 2013 comparisons, which were promising with regard to the effect of the TTED to reduce the catch of non-target species of sharks, snappers, flounders, lobsters, sponges, jellyfish and of, the target species shrimp.

Elasmobranch Bycatch - The 2013 comparisons confirmed the observations from 2012 regarding the TTED's ability to reduce shark bycatch. In 2013, the TTED-equipped trawl captured only a few small sharks (excluding deep water sharks), while the TED-equipped trawl captured over 250 sharks of several species (Table 31). Most of these sharks were captured while on the Key West fishing grounds. During the four days of fishing for Royal Red Shrimp in deep waters off Key West, Fringefin Lanternshark *Etmopterus schultzi* and the Marbled Catshark *Galeus arae* were frequent in the bycatch of both the TTED-equipped trawl and TED-equipped trawl. Fringefin Sharks larger than 40 cm were equally abundant in the TTED-equipped trawl relative to the TED-equipped trawl catch.

While fishing north of the Key West, one tow contained 67 sharks. This was the highest number of sharks encountered in a single tow during the 2013 comparisons. These were mostly Atlantic Sharpnose Sharks and a few Blacknose Sharks. These sharks were all caught in the TED-equipped trawl, and on this particular tow, while no sharks were captured by the TTED-equipped trawl. In a few tows the TED-equipped trawl catch contained four to seven Blacknose Sharks, with none in the TTED-equipped trawl. The fork length of individuals captured by the TED-equipped trawl ranged from 60-80 cm, with a majority of individuals in the upper size range. During the entire Key West portion of the trip (24 days and ~45 tows) there were over 40 Blacknose Sharks caught by the TED-equipped trawl, while the TTED-equipped trawl caught none. In this same area we captured seven Butterfly Rays *Gymnura micrura* and 15 other rays (*Raja* spp.) in the TED-equipped trawl, with no rays captured in the TTED-equipped trawl.

Fish Bycatch - Large snappers (>30 cm) were less frequent in the TTED-equipped trawl catch in the 2013 field season. During the 2013 trip, we encountered Red Snapper in the northern GOM, while in the Key West area we encountered Mutton Snapper *Lutjanus analis*. The TTED-equipped trawl and the TED-equipped trawl captured individuals of both species smaller than 25 cm, but the TTED-equipped trawl captured few that measured greater than 25 cm, and none that were greater than 35 cm. The largest Red Snapper caught in the TED-equipped trawl was an individual of 10.5 kg whereas the largest Red Snapper caught on the TTED-equipped trawl weighed ~450 g. On a few occasions, we caught 20 to 30 large (>35 cm) snappers in the TED-equipped trawl with none in the TTED-equipped trawl. In most tows with numerous small snappers present, there were comparable numbers in both experimental trawls.

Other fishes were also caught less frequently in the TTED-equipped trawl then in the TED-equipped trawl catch (Table 31). These included Cobia, Hognose Wrasse *Lachnolaimus maximus,* Gafftop Catfish *Bargus marinus*, Gulf Flounder, large sea robins, large lizardfishes and large Spanish Mackerel. For these fishes, specimens that were captured by the TED-equipped trawl were generally larger than those captured by the TTED-equipped trawl.

Invertebrate Bycatch - I observed a noticeable reduction in the capture of several invertebrates for the TTED-equipped trawl relative to the TED-equipped trawl. In both the northern GOM and near Key West, catches of crabs, lobsters, sponges, and jellyfish were less prevalent in the TTED-equipped trawl relative to the TED-equipped trawl. In the northern GOM, larger Rooster Crabs, Blue Crabs and Slipper Lobsters *Scyllarides nodifer* were less frequently observed in the catch of the TTED-equipped trawl relative to the TED-equipped trawl. In the Key West area, I observed that both the TTED-equipped trawl and TED-equipped trawl captured small spiny lobster; whereas larger individuals were excluded from the TTED-equipped trawl.

Over the course of the trip, at least 150 large spiny lobsters (cephalothoracic length greater than three inches) were retained by the TED-equipped trawl, whereas the TTED-equipped trawl did not seem to retain them.

Sponges were frequently encountered in and around the Key West fishing grounds and 2013 observations indicated that the TTED was effective at reducing their capture. There were occasions on which the TED-equipped trawl captured large mounds of sponges whereas the TTED-equipped trawl catch contained only small fragments of sponge. There were manyl tows with several kilograms of sponge contained in the TED-equipped trawl subsample relative to a few hundred grams in the TTED-equipped trawl subsample.

While large sponge catches in the TED-equipped trawl did not appear to affect shrimp retention, the same cannot be said about Moon Jellyfish *Aurelia aurita* which, when abundant, seemed to contribute to shrimp loss. During a ten-day period near Key West, we observed very high densities of Moon Jellyfish, which led to substantial operational challenges for the crew. Jellyfish can become stuck in the trawl codend and block water from filtering through the mesh. This causes the doors, which would normally spread out keeping the mouth of the trawl open, to be pulled together, reducing the width of the area covered by the trawl and inevitably reducing the number of shrimp captured by the TED-equipped trawl. In contrast, there were few jellyfish in the TTED-equipped trawl, presumably because they could not pass into the codend through the two-inch bar spacing. Jellyfish did not appear to collect in front of the TTED or TED and damage to the gear was not observed even when Moon Jellyfish catches in the TED-equipped trawl codend were very large.

Shrimp Catch. During the 2013 comparisons, shrimp production seemed to fluctuate without obvious trends between the TED-equipped trawl and TTED-equipped trawl, although small but statistically significant differences would be hard to notice in the field. However, at the captain's request while at sea I compiled data from the first 20 tows targeting Brown Shrimp. At that time, I had data from eleven tows with the TTED on one side of the boat and nine with the TTED on the other side. This preliminary analysis showed a 0.8% difference in shrimp production in favor of the TED. In contrast, during the ten-day portion of the comparisons in which many jellyfish were encountered the TTED-equipped trawl clearly caught more shrimp than did the TED-equipped trawl.

Discussion

Qualitative observations between the TED-equipped trawl and TTED-equipped trawl indicated that the bycatch retention of large animals (sharks, rays, big fishes) was greatly reduced with the TTED-equipped trawl due to a physical restriction— as the smaller bar spacing on the TTED did not allow an animal wider than two inches to pass through the grid. Very few sharks and snappers longer than 50 cm and 35 cm, respectively, were observed in the TTED-equipped trawl. When large fish did manage to pass through the TTED-equipped trawl, distinct scrape marks and missing scales were observed on these animals, presumably the consequence of squeezing through the 50 mm bar spacing. In contrast to large fish, small fish bycatch was not effectively reduced by the TTED-equipped trawl. Other animals that were excluded from the TTED-equipped trawl were invertebrates, including sponges. Though sponges were sometimes numerous in the catch, and were time-consuming for the crew to sort through, they did not seem to affect the shrimp catch from the TED-equipped trawl. Encounters with Moon Jellyfish, however, were both devastating to the shrimp production and very time-consuming for the crew.

Of particular interest to the fishermen was the TTED's capacity to drastically reduce jellyfish bycatch. When numerous jellyfish were found in the try net (a small sampling trawl used to infer what is caught by the larger trawls), the captain would generally elect to haul in the trawls, and move to a new location, to prevent the codends from ripping off from the weight of too many jellyfish. At times the captain elected to 'fish through' the jellyfish, which resulted in considerable shrimp loss for the TED-equipped trawl in comparison with the TTED-equipped trawl. Since jellyfish were evacuated from the trawl by the TTED they did not accumulate in the codend, allowing the trawl to maintain optimal fishing configuration. These observations indicated that TTEDs could have allowed the captain to fish normally even at times were large volumes of moon jellyfish were present, potentially allowing full-length tows.

In addition, the large volumes of jellyfish, once on the back deck, were very hard to handle. When the boat would tilt with the waves, all of the catch would slosh back and forth and it was practically impossible to separate the sorted portion of the catch from the unsorted portion of the catch. Crew would often elect to open a gunnel and pick out shrimp as best they could as the jellyfish oozed off the back deck. This precarious technique resulted in a considerable volume of shrimp lost overboard with the jellyfish from the TED-equipped trawl.

Small fish bycatch did not seem to be reduced by the TTED-equipped trawl except in situations where the TTED angle was reduced. The results of this study suggests that the TTED's effectiveness at retaining shrimp and reducing bycatch may be sensitive to the angle at which the TTED hangs in the trawl during the fishing operations (as noted in Chapter 2). When the TTED was at the optimal angle setting (50°- 55°), the gear performed very well, and in some cases outperformed the TED in terms of commercial shrimp catch. When the TTED was inclined to 45° or less, however, shrimp catches decreased. Water passing between bars can experience interference when the spacing it narrow or approaching critical gap (Harichandan et al. 2010, Zhou et al. 2000). I speculate that flow interference of the TTED may increase at low angles, in turn hindering flow through the device. This flow interference may cause a diversion of water flow toward the TTED opening, eventually forcing the TTED exit hole covering open and allowing a portion of the catch, including shrimp and small fish, to escape. Though TTEDs incorporating stretch-resistant webbing were purchased new, there were three separate instances in which the TTED angle had to be adjusted, twice while at sea (GA and AL) and once before starting the MS experiment. The TED used in MS was bought with an angle that measured 49°, highlighting the importance of checking TED angles regularly even when purchased new from the manufacturer.

Another incident that may be an important consideration was the observed warping of one TTED when the catch was mainly composed of shells. After consultation with the captain and crew, they explained that the shells captured in the codend indicated that during the fishing process the trawl had dug into the substrate and a large volume of sediment-containing shells was forced through the TTED. While towing, the soft substrate washed out of the codend leaving only the shells. I have heard oral accounts but have not encountered written reports describing trawls digging into substrate to this degree. Therefore, I do not know if this is a tendency that could reduce the TTED's, TED's or both gears' effectiveness under commercial shrimping operations.

The 2013 fall comparisons were very rich in results. The TTED was evaluated in a variety of GOM offshore shrimping conditions and was tested on four commercially targeted shrimp species. Overall, there appeared to be a dramatic decrease in the number of elasmobranchs caught by the TED-equipped trawl relative to the TTED-equipped trawl, confirming observations from the 2012 field season. For sharks, specifically Blacknose Sharks, the TTED-equipped trawl showed a much higher rate of exclusion from capture than did the TED-equipped trawl.

As predicted by captains, many more sharks and larger fishes were encountered in the fall. The TTED-equipped trawl seemed to be more effective than the TED-equipped trawl for the reduction of sharks and snappers larger than 30 cm. The TTED also seemed to be very useful when large quantities of sponges and jellyfish were encountered.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

The 2012 and 2013 TTED and TED comparisons were conducted in a variety of offshore shrimping conditions; being tested once on the U.S. Atlantic east coast and three times in the Gulf of Mexico, on four commercially targeted shrimp species. My research indicated that TTED-equipped trawls largely reduced elasmobranch catch and maintained shrimp catch when compared to TED-equipped trawls in the Gulf of Mexico. The TTED may be a good BRD candidate for reducing bycatch of larger fishes. This has implications for management of U.S. Shrimp Trawl (ST) fisheries since the stock assessment for Blacknose Sharks suggests the species is overfished and concurrently experiencing high bycatch mortality from shrimp trawls (SEDAR 21). If it becomes possible to predict times and areas where Blacknose Sharks are vulnerable to ST bycatch, the TTED could serve as a BRD capable of reducing the capture of this species. This would help fulfill the NMFS Highly Migratory Species Management Division's obligations to implement actions to reduce the bycatch of Blacknose Sharks by U.S. shrimp trawls.

Though small fish bycatch was not reduced by the TTED, this gear may represent a better option for the shrimp trawl industry than the TED, since comparisons under commercial situations suggest that the TTED catches equivalent shrimp weight and reduced more bycatch than the TED.

Though catches of larger fish including Red Snapper, sharks, rays and skates, in addition to jellyfish and debris, were reduced by the TTED relative to the TED, continued bycatch research is necessary to confirm these findings. The TTED serves as an example of how a simple innovation in bycatch technology may improve the efficiency of an already well-established device. The potential for interest and application of this device within U.S. shrimp fisheries is demonstrated by the adoption of the TTED or a modification of it (i.e. reduced bar spacing) by 3 of the captains who participated in this study.

This study indicated that the TTED is similar to the TED in its efficiency or lack there of reducing small fish bycatch. According to Raborn et al. 2012, TEDs reduced 5-13% of small fish bycatch. This study also indicated that the TTED, like the TED was effective at not catching turtles and caused minimal reductions in shrimp catches (Renaud et al. 1993 and Broadhurst 2000). Concerning Red Snapper, studies by Engass et al 1999 showed that red snapper are difficult to remove passively from the trawls with BRDs but the TTED seems to be more effective than the TED at reducing individuals larger then 30cm and this may have implications for the recovery of this species. Finally this study addressed the problem raised by Raborn et al. 2012 concerning current TEDs and other BRDs inability to significantly reduce small elasmobranch bycatch. In contrast, the TTED seems to be effective at reducing small elasmobranch bycatch.

The results of this study helped to identify factors that require further investigation, and several questions have been developed to guide future reduced bar spacing TED research. The following recommendations are based on discussions with participating shrimp fishery captains, and at-sea observations during the TTED study.

Research questions with ecological considerations:

- Do TEDs with 2.25-inch (5.7cm) or 2.5-inch (6.3cm) bar spacing reduce shark bycatch equal to or greater than the TTED?
- How can TTED use influence projected Blacknose Shark population recovery?
- What is the range of Red Snapper length caught by the TTED, and how can TTED use influence projected Red Snapper population recovery?
- How does TTED angle affect catches of small fish bycatch? What are the associated influences on target shrimp catch at reduced TTED angles?

- Can the TTED be used at a 60° or 65° angle of inclination and still effectively evacuate turtles from the trawl?

Research questions with economic considerations:

- Does a 2-inch TTED have greater drag than the 2.5-inch, 3-inch or 4-inch TED? How do these changes in drag affect fuel usage and operating costs?
- Does the lower drag from the TTEDs "cleaner" catch compensate for the increased drag from the reduced bar spacing as compared to the TED?
- Does the TTED systematically lose shrimp at an of inclination angle of 45°?
- How often would shrimpers need to readjust their TTED to maintain optimal angle configuration, as compared to a TED? What additional costs would this incur?

My final recommendation would be to repeat the fall TTED and TED comparison study in the Key West Pink Shrimp fishery because of the promise that the TTED demonstrated in simultaneously reducing bycatch of multiple species, which largely reduced the crew's work load and therefore increased efficiency in this fishery.

APPENDIX

LIST OF ACRONYMS

BRD	Bycatch Reduction Device
CPUE	Catch Per Unit Effort
EEZ	Exclusive Economic Zone
Emsy	Cost of effort at MSY
FAO	Food and Agricultural Administration
FSD	Finfish Separator Device
GA	Georgia
GLMM	Generalized Linear Mixed Model
GMFMC	Gulf of Mexico Fishery Management Council
GOM	Gulf of Mexico
GSFF	Gulf and South Atlantic Fisheries Foundation
KMT	Thousand Metric Ton
MEY	Maximum Economic Yield
MMT	Million Metric Ton
MS	Mississippi
MSA	Magnuson Stevens Fishery Management Act
MSY	Maximum Sustainable Yield
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
OGSF	Offshore Gulf of Mexico Shrimp Trawl Fishery
RES	Radial Escape Section
SAB	South Atlantic Bight
SAFMC	South Atlantic Fishery Management Council
SEFSC	South East Fisheries Science Center
SEWG	Shrimp Effort Working Group
ST	Shrimp Trawl
TAC	Total allowable catch
TED	Turtle Excluder Device
TTED	Trash and Turtle Excluder Device
TX	Texas
VPA	Virtual Population Analysis

TABLES

Table 1. Correlation Between Variables

Variables were tested for correlation for Georgia (GA), Texas (TX) and Mississippi (MS). X marks correlated variables as determined by significant p-values. Tow time is the duration of a tow in minutes, Tow depth is the average tow depth for a given tow, Big fish bycatch (#) is the number of all big animals caught in the TTED-equipped trawl minus the number of all big animals caught in the TED-equipped trawl. Big Fish bycatch & debris reduction (kg) is the weight of all big animal bycatch plus the weight of debris from the TTED-equipped trawl minus the weight of all big animal bycatch plus the weight of debris from the TED-equipped trawl, Total croaker reduction (kg) is the total croaker weight from the TTED-equipped trawl minus the total croaker weight from the TED-equipped trawl.

GA	Model variables	Tow time	Tow depth	Big fish bycatch (#)	Big fish bycatch & debris reduction (kg)	Total croaker reduction (kg
	Tow depth					
	Big fish bycatch reduction (#)		X			
	Big fish bycatch and debris reduction (kg)		X	X		
	Total croaker reduction (kg)					
	Total bycatch reduction (kg)			X	X	
TX	Model variables	Tow time	Tow depth	Big fish bycatch (#)	Big fish bycatch and debris reduction (kg)	Total croake reduction (kg
	Tow depth					
	Big fish bycatch and debris reduction (#)					
	Big fish bycatch and debris reduction (kg)			X		
	Total croaker reduction (kg)					
	Total bycatch reduction (kg)					
MS	Model variables	Tow time	Tow depth	Big fish bycatch (#)	Big fish bycatch and debris reduction (kg)	Total croake reduction (kg
	Tow depth					
	Big fish bycatch and debris reduction (#)					
	Big fish bycatch and debris reduction (kg)					
	Total croaker reduction (kg)					
	Total bycatch reduction (kg)					X

Table 2. Dates and Locations of the 2012 Gear Comparison Cruises.

Port	Dates	Days-at-Sea	Valid Tows
Darien, GA	May 14-27	13	31
Freeport, TX	June 27-July 28	32	44
Pascagoula, MS	August 2-27	26	35
TOTAL		71	110

Table 3. Technical Characteristics of Fishing Vessels and Trawls Used in the 2012 TTED versus TED Comparisons.

Cruises occurred off Georgia (GA) in the U.S. South Atlantic Bight and off Texas (TX) and Mississippi (MS) in the Gulf of Mexico.

Gear Differences	**GA**	**TX**	**MS**
Vessel length (m)	24.4	25	32
Main engine power (Hp)	365	540	855
Main engine make	General Motors	Caterpillar	Caterpillar
Doors type	Wood	Cambered Steel	Aluminum
Door Length & width (m)	2.44, 1.02	3.35, 1.06	1.49, 1.22
Bridal length (m) and type	76 Steel	109.44 Dynema	109.44 Steel
Head rope length	15.24	17.07	18.9
Trawl type and tow speed (kn)	Bib, 2.9	Balloon, 2.8	Flat 2.9
BRD active	Yes (Fisheye)	No	No
Control TED shape	Oval	Square bottom	Oval
Accelerator funnel	No	Yes	Yes

Table 4. Tow Characteristics of the 2012 TTED versus TED Comparisons.
GA refers to the cruise from Georgia, TX refers to the cruise from Texas, MS refers to the cruise from Mississippi, GOM refers to the Gulf of Mexico.

Tow Characteristics	GA	TX	MS
Day or night fishing	day	night	night
Maximum tow depth (m)	12.19	72.24	86.56
Average tow depth (m)	7.8	54.5	37.3
Minimum tow depth (m)	3.35	38.59	25.6
Number of tows	35	71	43
Number of valid tows	31	44	35
Tow # on port vs starboard	17 , 14	21, 23	17, 18
Total hours towed	100h54min	212h12min	118h 24min
Maximum tow time (hr)	5:05	8:25	5:25
Average tow time (hr)	3:21	4:55	3:23
Minimum tow time (hr)	1:31	1:58	2:40
Number of tows per day	4	2	2 or 3
Number of tows per day	4	2	2 or 3
Area fished (in fig #)	East Coast	East GOM LA/MS	West GOM LA, TX

Table 5. Total Catch Weights and CPUEs by Cruise.

Data are presented as the sum of the target and bycatch weights for all valid tows for the TED-equipped trawl (kg TED) and TTED-equipped trawl (kg TTED) by cruise. The two CPUE (kg/hr) columns refer to the total catch weight from the TED-equipped trawl (total catch TED /total hours towed) and the TTED-equipped trawl (total catch TTED/total hours towed). Kg diff is the difference in total catch weight of the TED-equipped trawl relative to the TTED-equipped trawl (kg TTED minus kg TED). % diff is the percent difference in total catch weight of the TED-equipped trawl relative to the TTED-equipped trawl.

Cruise	kg TED	kg TTED	CPUE TED	CPUE TTED	Kg diff	% diff
GA	5200.85	3158.62	51.5616	31.3148	-2042.23	-39.27%
TX	10716.49	10584.38	49.3128	48.7049	-132.11	-1.23%
MS	8238.01	7657	71.4485	66.4094	-581.01	-7.05%

Table 6. Shrimp Weights and CPUEs by Cruise.

Data are presented as the number of tows in which the species was encountered (Freq). The sum of the shrimp weight for all valid tows for the TED-equipped trawl (kg TED) and TTED-equipped trawl (kg TTED) by cruise. The two CPUE (kg/hr) columns refer to the total shrimp weight from the TED-equipped trawl (total species' weight TED/total hours towed) and the TTED-equipped trawl (total species' weight TTED/total hours towed). Kg diff is the difference in total shrimp weight of the TED-equipped trawl relative to the TTED-equipped trawl (kg TTED minus kg TED). % diff is the percent difference in total shrimp weight of the TED-equipped trawl relative to the TTED-equipped trawl.

Cruise	Species	freq	Kg TED	Kg TTED	CPUE TED	CPUE TTED	kg diff	% diff
GA	White Shrimp	31	856.3	824	8.342	7.982	-0.36	-4.32%
TX	Brown Shrimp	44	2895.22	3058.46	13.628	14.455	0.827	6.07%
MS	Brown Shrimp	34	1653.35	1633	14.582	14.352	-0.23	-1.58%

Table 7. Shrimp Weight CPUE T-test by Cruise.

Data are presented as estimates of the mean CPUE (kg/hr) difference in shrimp weight from the TTED-equipped trawl relative to the TED-equipped trawl, standard error (StdErr) of the mean, standard deviation (StdDev) from the mean, t-value, degrees of freedom (DF), and p-value. Significant differences of species weight CPUEs (p<0.05) are in bold.

Cruise	Species	Mean	StdDev	StdErr	t-value	DF	p-value
GA	White Shrimp	0.360	0.976	0.175	2.053	30	**0.0489**
TX	Brown Shrimp	-0.827	2.066	0.311	-2.655	43	**0.0111**
MS	Brown Shrimp	0.230	1.801	0.309	0.746	33	0.4611

Table 8. Species Catch Weights and CPUEs for the Georgia Cruise.

Data are presented as the number of tows in which the species was encountered (Freq). The sum of the species' weight for all valid tows for the TED-equipped trawl (kg TED) and TTED-equipped trawl (kg TTED) by cruise. The two CPUE (kg/hr) columns refer to the total species' weight from the TED-equipped trawl (total species' weight TED /total hours towed) and the TTED-equipped trawl (total species' weight TTED/total hours towed). Kg diff is the difference in total species' weight of the TED-equipped trawl relative to the TTED-equipped trawl (kg TTED minus kg TED). % diff is the percent difference in total species' weight of the TED-equipped trawl relative to the TTED-equipped trawl. Atlantic Sharpnose (small) refers to neonate Atlantic Sharpnose Sharks that were kept separate from adult Atlantic Sharpnose Sharks (Atlantic Sharpnose).

Common Name	Freq	TED kg	TTED kg	CPUE TED	CPUE TTED	kg diff	% diff
Atlantic Sharpnose	26	481.8	0.45	5.69	0.00	-5.68	-99.9%
Atlantic Sharpnose (Small)	19	104.6	62.7	1.71	1.00	-0.70	-41.1%
Blacknose Shark	9	5.5	0.4	0.18	0.01	-0.17	-93.4%
Bonnethead Shark	14	54.55	0.4	1.23	0.01	-1.22	-99.3%
Blacktip Shark	3	7.35	0	0.61	0.00	-0.61	-100.0%
Scalloped Hammerhead	5	2.6	0.2	0.18	0.02	-0.16	-91.1%
Smoothed Hammerhead	2	3.7	0.25	0.78	0.03	-0.75	-96.1%
Ray & Skate	11	20.1	2	0.63	0.04	-0.59	-93.4%
Winter Flounder	1	0.4	0	0.18	0.00	-0.18	-100.0%
Spanish Mackerel	4	1.25	0.42	0.11	0.03	-0.08	-74.3%
Horseshoe Crab	19	121	0	1.97	0.00	-1.97	-100.0%
Fishes (unclassified) and jellyfish	30	3541.7	2267.8	36.86	23.23	-13.63	-37.0%

Table 9. Species Catch Weights and CPUEs for the Texas Cruise.

Data are presented as the number of tows in which the species was encountered (Freq). The sum of the species' weight for all valid tows for the TED-equipped trawl (kg TED) and TTED-equipped trawl (kg TTED) by cruise. The two CPUE (kg/hr) columns refer to the total species' weight from the TED-equipped trawl (total species' weight TED /total hours towed) and the TTED-equipped trawl (total species' weight TTED/total hours towed). Kg diff is the difference in total species' weight of the TED-equipped trawl relative to the TTED-equipped trawl (kg TTED minus kg TED). % diff is the percent difference in total species' weight of the TED-equipped trawl relative to the TTED-equipped trawl.

Species	Freq	Kg TED	Kg TTED	CPUE TED	CPUE TTED	kg diff	% diff
Atlantic Sharpnose	16	48.65	2.9	0.68	0.04	-0.63	-93.36%
Blacknose Shark	1	2.1	0	0.41	0.00	-0.41	-100.00%
Dusky Shark	1	1.55	0	0.37	0.00	-0.37	-100.00%
Gulf Smoothhound	39	35.8	23.85	0.19	0.13	-0.06	-32.24%
Atlantic Angle Shark	5	2.35	0.35	0.12	0.02	-0.10	-85.89%
Rays & Skates	7	10.1	2.15	0.29	0.07	-0.22	-76.52%
Red Snapper	36	69.7	56.6	0.42	0.33	-0.09	-21.00%
Vermillion Snapper	4	12.9	9.95	0.59	0.44	-0.15	-24.65%
Wenchman Snapper	44	362.8	356.79	1.71	1.67	-0.04	-2.41%
Lane Snapper	2	1.72	1.51	0.17	0.14	-0.02	-13.48%
Southern Flounder	2	1.15	0	0.10	0.00	-0.10	-100.00%
Atlantic Croaker	44	819.63	791.35	3.95	3.81	-0.14	-3.49%
Blackear Bass	9	71.52	23.24	1.50	0.47	-1.03	-68.72%
Butterfish	17	247.02	341.41	3.06	4.34	1.28	41.99%
Cutlas Fish	4	19.53	20.39	0.87	1.10	0.23	26.88%
Sea Trouts	40	137.84	136.47	0.72	0.71	-0.01	-1.45%
Lizardfishes	30	288.43	360.74	1.85	2.34	0.49	26.34%
Longspine Porgy	44	1419.17	1433.63	7.08	6.98	-0.10	-1.47%
Oscillated Flounder	2	8.69	15.26	0.71	1.80	1.08	52.73%
Rock Seabass	21	149.57	155.81	1.42	1.47	0.05	3.69%
Rough Scad	34	610.52	653.95	4.04	4.27	0.22	5.56%
Sea Robins	11	66.26	61.91	1.26	1.17	-0.09	-7.00%
Spot	1	53.51	48.34	10.92	9.87	-1.06	-9.66%
Fishes (unclassified)	44	1668.27	1532.03	7.87	7.22	-0.65	-8.27%
Crustaceans (unclassified)	44	966.52	773.63	4.39	3.49	-0.89	-20.39%
Shrimp Discard	43	25.67	21.35	0.12	0.10	-0.02	-12.87%
Invertebrates (unclassified)	44	672.94	665.96	3.05	3.01	-0.04	-1.28%
Debris	36	41.74	36.35	0.23	0.22	-0.01	-6.35%

Table 10. Species Catch Weights and CPUEs for the Mississippi Cruise.

Data are presented as the number of tows in which the species was encountered (Freq). The sum of the species' weight for all valid tows for the TED-equipped trawl (kg TED) and TTED-equipped trawl (kg TTED) by cruise. The two CPUE (kg/hr) columns refer to the total species' weight from the TED-equipped trawl (total species' weight TED /total hours towed) and the TTED-equipped trawl (total species' weight TTED/total hours towed). Kg diff is the difference in total species' weight of the TED-equipped trawl relative to the TTED-equipped trawl (kg TTED minus kg TED). % diff is the percent difference in total species' weight of the TED-equipped trawl relative to the TTED-equipped trawl. Lizardfishes (large) includes individuals that weighed 300g or more. Lizardfishes (small) included individuals that weighed less than 300g. Sea Robins (large) includes individuals that weighed 175g or more. Sea Robins (small) includes individuals that weighed less than 175g. Crabs (large) includes individuals that weighed more 200g of more.

Species	Freq	Kg TED	Kg TTED	CPUE TED	CPUE TTED	kg diff	% diff
Atlantic Sharpnose	3	15	3	1.52	0.31	-1.22	-79.81%
Gulf Smoothhound	4	9.81	0.5	0.59	0.03	-0.56	-95.22%
Rays & Skates	10	6.6	0.8	0.20	0.03	-0.17	-86.84%
Red Snapper	25	36.32	13.34	0.46	0.18	-0.28	-61.31%
Wenchman Snapper	5	15.63	10.27	0.85	0.57	-0.28	-33.26%
Whitings	5	6.92	0.93	0.46	0.05	-0.40	-88.70%
Louisiana Redfish	1	9.75	0	3.25	0.00	-3.25	-100.00%
Southern Flounder	7	4.09	0.29	0.17	0.02	-0.16	-91.14%
Spanish Mackerel	2	0.9	0	0.14	0.00	-0.14	-100.00%
Atlantic Croaker	34	2842.33	2769.94	25.08	24.73	-0.36	-1.43%
Butterfish	7	47.32	39.51	1.94	1.62	-0.33	-16.76%
Sea Trouts spp	34	221.3	166.58	1.92	1.44	-0.48	-24.94%
Lizardsfishes spp (small)	16	151.79	172.25	2.76	3.11	0.36	12.90%
Lizardsfishes spp (large)	7	22.65	0	0.82	0.00	-0.82	-100.00%
Longspine Porgy	34	911.02	885.57	7.87	7.69	-0.17	-2.21%
Red Porgy	2	0	1.41	0.00	0.19	0.19	100.00%
Sea Robins (large)	13	75.19	10.13	1.71	0.23	-1.48	-86.63%
Sea Robins (small)	16	191.98	188.33	3.46	3.35	-0.12	-3.38%
Spot	28	170.7	239.17	1.86	2.58	0.72	38.55%
Fishes (unclassified)	34	993.51	904.03	8.96	8.23	-0.73	-8.13%
Crabs (large)	15	54.08	6.05	1.04	0.11	-0.93	-89.63%
Crustaceans (unclassified)	34	620.8	513.7	5.40	4.46	-0.94	-17.45%
Shrimp Discard	27	6.65	7.87	0.07	0.08	0.01	20.05%
Invertebrates (unclassified)	26	45.63	64.16	0.54	0.79	0.25	46.65%
Debris	21	120.64	26.17	1.97	0.40	-1.57	-79.71%

Table 11. Species Catch Numbers (Counts) and CPUEs for the Georgia Cruise.
Data are presented as the number of tows in which the species was encountered (Freq). The sum of the species' number (count) for all valid tows for the TED-equipped trawl (# TED) and TTED-equipped trawl (# TTED) by cruise. The two CPUE (number of individuals caught/hr) columns refer to the total species' number (count) from the TED-equipped trawl (total species' number TED /total hours towed) and the TTED-equipped trawl (total species' number TTED/total hours towed). # diff is the difference in total species' number (count) of the TED-equipped trawl relative to the TTED-equipped trawl (# TTED minus kg # TED). % diff is the percent difference in total species' number (count) of the TED-equipped trawl relative to the TTED-equipped trawl. Atlantic Sharpnose (small) refers to neonate Atlantic Sharpnose Sharks that were kept separate from adult Atlantic Sharpnose Sharks (Atlantic Sharpnose).

Species	Freq	# TED	# TTED	CPUE TED	CPUE TTED	# diff	% diff
Atlantic Sharpnose	26	172	1	2.04	0.01	-2.03	-99.46%
Atlantic Sharpnose (small)	19	743	459	12.06	7.32	-4.74	-39.34%
Blacknose Shark	9	10	1	0.32	0.03	-0.29	-90.79%
Blacktip Shark	3	3	0	0.24	0.00	-0.24	-100.00%
Bonnethead Hammerhead	14	30	1	0.69	0.02	-0.67	-97.02%
Horseshoe Crab	19	81	0	1.30	0.00	-1.30	-100.00%
Rays & Skates	11	15	1	0.47	0.02	-0.45	-95.56%
Scalloped Hammerhead	5	6	1	0.40	0.08	-0.32	-79.77%
Smoothed Hammerhead	2	2	1	0.35	0.12	-0.23	-65.24%
Spanish Mackerel	4	4	2	0.34	0.13	-0.21	-61.56%
Winter Flounder	1	1	0	0.45	0.00	-0.45	-100.00%
Fishes (unclassified) and jellyfish	30	NA	NA				

Table 12. Species Catch Numbers (Counts) and CPUEs for the Texas Cruise.

Data are presented as the number of tows in which the species was encountered (Freq). The sum of the species' number (count) for all valid tows for the TED-equipped trawl (# TED) and TTED-equipped trawl (# TTED) by cruise. The two CPUE (number of individuals caught/hr) columns refer to the total species' number (count) from the TED-equipped trawl (total species' number TED /total hours towed) and the TTED-equipped trawl (total species' number TTED/total hours towed). # diff is the difference in total species' number (count) of the TED-equipped trawl relative to the TTED-equipped trawl (# TTED minus kg # TED). % diff is the percent difference in total species' number (count) of the TED-equipped trawl relative to the TTED-equipped trawl.

Species	Freq	# TED	# TTED	CPUE TED	CPUE TTED	# diff	% diff
Atlantic Sharpnose	16	28	3	0.36	0.05	-0.32	-87.02%
Blacknose Shark	1	1	0	0.20	0.00	-0.20	-100.00%
Dusky Shark	1	1	0	0.24	0.00	-0.24	-100.00%
Gulf Smoothhound	39	62	43	0.34	0.24	-0.09	-28.24%
Atlantic Angle Shark	5	5	1	0.23	0.05	-0.19	-79.73%
Rays & Skates	7	14	11	0.40	0.34	-0.06	-15.08%
Red Snapper	36	424	426	2.58	2.49	-0.09	-3.51%
Vermillion Snapper	4	415	299	18.79	13.46	-5.33	-28.35%
Wenchman Snapper	44	11164	11116	52.71	52.04	-0.67	-1.28%
Lane Snapper	2	35	10	3.41	0.95	-2.45	-72.04%
Shrimp Discard	43	8214	6119	37.37	28.25	-9.12	-24.40%
Atlantic Croaker	44	11393	11208	54.91	53.92	-0.99	-1.80%
Blackear Bass	9	11159	3291	229.97	66.82	-163.15	-70.94%
Butterfish	17	3613	5085	44.86	64.82	19.96	44.49%
Cutlass Fish	4	273	272	12.15	14.43	2.28	18.75%
Spot	1	561	501	114.49	102.24	-12.24	-10.70%
Lizardfishes	30	2300	3099	15.07	20.24	5.17	34.30%
Longspine Porgy	44	29790	30544	149.51	149.63	0.11	0.08%
Oscillated Flounder	2	111	40	9.07	4.71	-4.37	-48.14%
Rock Seabass	21	2676	3340	25.60	30.73	5.13	20.05%
Rough Scad	34	24738	27587	166.72	180.05	13.33	7.99%
Sea Robins	11	1715	1643	32.19	30.62	-1.57	-4.87%
Southern Flounder	2	2	0	0.17	0.00	-0.17	-100.00%

Table 13. Species Catch Numbers (Counts) and CPUEs for the Mississippi Cruise.

Data are presented as the number of tows in which the species was encountered (Freq). The sum of the species' number (count) for all valid tows for the TED-equipped trawl (# TED) and TTED-equipped trawl (# TTED) by cruise. The two CPUE (number of individuals caught/hr) columns refer to the total species' number (count) from the TED-equipped trawl (total species' number TED /total hours towed) and the TTED-equipped trawl (total species' number TTED/total hours towed). # diff is the difference in total species' number (count) of the TED-equipped trawl relative to the TTED-equipped trawl (# TTED minus kg # TED). % diff is the percent difference in total species' number (count) of the TED-equipped trawl relative to the TTED-equipped trawl. Lizardfishes (large) include individuals that weighed 300g or more. Lizardfishes (small) included individuals that weighed less than 300g. Sea Robins (large) includes individuals that weighed 175g or more. Sea Robins (small) includes individuals that weighed less than 175g. Crabs (large) includes individuals that weighed more 200g of more.

Species	Freq	# TED	# TTED	CPUE TED	CPUE TTED	# diff	% diff
Atlantic Sharpnose	3	5	1	0.51	0.10	-0.41	-79.81%
Gulf Smoothhound	4	6	1	0.38	0.06	-0.33	-85.26%
Rays & Skates	10	12	2	0.35	0.06	-0.29	-81.65%
Red Snapper	25	101	82	1.25	1.01	-0.24	-19.37%
Wenchman Snapper	5	551	326	30.01	18.01	-12.00	-40.00%
Whitings	5	41	9	2.62	0.48	-2.14	-81.77%
Louisiana Redfish	1	1	0	0.33	0.00	-0.33	-100.00%
Southern Flounder	7	8	1	0.35	0.05	-0.30	-85.13%
Spanish Mackerel	2	2	0	0.31	0.00	-0.31	-100.00%
Atlantic Croaker	34	61320	59129	541.22	529.21	-12.01	-2.22%
Butterfish	7	502	326	20.63	13.01	-7.62	-36.94%
Sea Trouts	34	2446	1800	21.22	15.58	-5.64	-26.57%
Lizardsfishes (small)	16	NA	NA	NA	NA	NA	NA
Lizardsfishes (large)	7	59	0	2.10	0.00	-2.10	-100.00%
Longspine Porgy	34	24669	24118	213.31	209.76	-3.56	-1.67%
Red Porgy	2	0	14	0.00	1.94	1.94	100.00%
Sea Robins (large)	13	234	42	5.31	0.94	-4.37	-82.32%
Sea Robins (small)	16	NA	NA	NA	NA	NA	NA
Spot	28	2879	4068	31.26	43.94	12.68	40.58%
Fishes (unclassified)	34	NA	NA	NA	NA	NA	NA
Crabs (large)	15	225	35	4.40	0.65	-3.75	-85.28%
Crustaceans (unclassified)	34	NA	NA	NA	NA	NA	NA
Shrimp Discard	27	1661	1974	16.39	19.78	3.38	20.63%
Invertebrates (unclassified)	26	NA	NA	NA	NA	NA	NA
Debris	21	NA	NA	NA	NA	NA	NA

Table 14. Species Weight CPUE *t*-test for the Georgia Cruise.

Data are presented as estimates of the mean CPUE (kg/hr) difference in shrimp weight CPUEs from the TTED-equipped trawl relative to the TED-equipped trawl, standard error (StdErr) around means, standard deviation (StdDev) from the mean, t-value, degrees of freedom (DF), and p-value. Significant differences of species weight CPUEs (p<0.05) are in bold. Atlantic Sharpnose (small) refers to neonate Atlantic Sharpnose Sharks that were kept separate from adult Atlantic Sharpnose Sharks (Atlantic Sharpnose). N/A indicates that data were unavailable due to the model not converging.

Species	Mean	StdDev	StdErr	t-value	DF	p-value
Winter Flounder	0.179	N/A	N/A	N/A	0	N/A
Atlantic Sharpnose	5.683	4.568	0.896	6.344	25	**<0.0001**
Horseshoe Crab	1.973	1.251	0.287	6.875	18	**<0.0001**
Fishes (unclassified)	13.628	15.258	2.786	4.892	29	**<0.0001**
Blacknose Shark	0.169	0.063	0.021	8.019	8	**<0.0001**
Bonnethead Hammerhead	1.224	1.216	0.325	3.767	13	**0.0023**
Rays & Skates	0.590	0.621	0.187	3.151	10	**0.0103**
Atlantic Sharpnose (small)	0.702	1.205	0.276	2.538	18	**0.0206**
Blacktip Shark	0.609	0.341	0.197	3.090	2	0.0907
Spanish Mackerel	0.080	0.082	0.041	1.932	3	0.1488
Scalloped Hammerhead	0.163	0.214	0.096	1.703	4	0.1638
Smoothed Hammerhead	0.748	0.901	0.637	1.174	1	0.4492

Table 15. Species Weight CPUE *t*-test for the Texas Cruise.

Data are presented as estimates of the mean CPUE (kg/hr) difference in shrimp weight CPUEs from the TTED-equipped trawl relative to the TED-equipped trawl, standard error (StdErr) around means, standard deviation (StdDev) from the mean, t-value, degrees of freedom (DF), and p-value. Significant differences of species weight CPUEs (p<0.05) are in bold. N/A indicates that data were unavailable due to the model not converging.

Species	Mean	StdDev	StdErr	t-value	DF	p-value
Dusky Shark	0.373	N/A	N/A	N/A	0	N/A
Spot	1.055	N/A	N/A	N/A	0	N/A
Blacknose Shark	0.413	N/A	N/A	N/A	0	N/A
Atlantic Sharpnose	0.632	0.617	0.154	4.099	15	**0.0009**
Crustaceans (unclassified)	0.894	1.709	0.258	3.471	43	**0.0012**
Fishes (unclassified)	0.651	2.051	0.309	2.107	43	**0.0410**
Lizardfishes	-0.487	1.279	0.233	-2.086	29	**0.0459**
Rays & Skates	0.220	0.239	0.090	2.433	6	0.0510
Gulf Smoothhound	0.063	0.204	0.033	1.925	38	0.0617
Blackear Bass	1.031	1.531	0.510	2.019	8	0.0781
Atlantic Angle Shark	0.101	0.133	0.059	1.699	4	0.1646
Southern Flounder	0.101	0.041	0.029	3.450	1	0.1796
Butterfish	-1.284	3.930	0.953	-1.347	16	0.1966
Shrimp Discard	0.016	0.101	0.015	1.005	42	0.3206
Red Snapper	0.088	0.579	0.097	0.907	35	0.3707
Vermillion Snapper	0.146	0.293	0.147	0.992	3	0.3944
Atlantic Croaker	0.138	1.985	0.299	0.461	43	0.6472
Rough Scad	-0.225	3.066	0.526	-0.427	33	0.6720
Wenchman Snapper	0.041	0.743	0.112	0.368	43	0.7146
Ocellated Flounder	-1.085	3.544	2.506	-0.433	1	0.7399
Longspine Porgy	0.104	2.265	0.341	0.305	43	0.7616
Cutlass Fish	-0.233	1.569	0.784	-0.297	3	0.7859
Debris	0.015	0.444	0.074	0.200	35	0.8423
Sea Robins	0.088	1.467	0.442	0.199	10	0.8461
Invertebrates (unclassified)	0.039	1.416	0.213	0.182	43	0.8563
Rock Seabass	-0.052	1.415	0.309	-0.170	20	0.8667
Lane Snapper	0.022	0.207	0.146	0.153	1	0.9032
Sea Trouts	0.010	0.749	0.118	0.088	39	0.9305

Table 16. Species Weight CPUE *t*-test for the Mississippi Cruise.

Data are presented as estimates of the mean CPUE (kg/hr) difference in shrimp weight CPUEs from the TTED-equipped trawl relative to the TED-equipped trawl, standard error (StdErr) around means, standard deviation (StdDev) from the mean, t-value, degrees of freedom (DF), and p-value. Significant differences of species weight CPUEs ($p<0.05$) are in bold. Lizardfishes (large) include individuals that weighed 300g or more. Lizardfishes (small) include individuals that weighed less than 300g. Sea Robins (large) include individuals that weighed 175g or more. Sea Robins (small) include individuals that weighed less than 175g. Crabs (large) includes individuals that weighed more 200g of more. Crabs (small) includes individuals that weighed less than 200g. N/A indicates that data were unavailable due to the model not converging.

Species	Mean	StdDev	StdErr	t-value	DF	p-value
Louisiana Redfish	3.250	N/A	N/A	N/A	0	N/A
Sea Robins (large)	1.478	0.977	0.271	5.454	12	**0.0001**
Crabs (large)	0.932	0.849	0.219	4.252	14	**0.0008**
Southern Flounder	0.155	0.095	0.036	4.299	6	**0.0051**
Rays & Skates	0.171	0.149	0.047	3.637	9	**0.0054**
Large Lizardfish	0.817	0.514	0.194	4.204	6	**0.0057**
Spot	-0.717	1.661	0.314	-2.284	27	**0.0304**
Red Snapper	0.280	0.638	0.128	2.192	24	**0.0383**
Crustaceans (unclassified)	0.942	2.925	0.502	1.879	33	0.0691
Spanish Mackerel	0.135	0.026	0.018	7.337	1	0.0862
Sea Trouts spp	0.480	1.719	0.295	1.627	33	0.1132
Gulf Smouthhound	0.563	0.515	0.258	2.186	3	0.1167
Red Porgy	-0.194	0.073	0.052	-3.752	1	0.1658
Shrimp Discard	-0.014	0.053	0.010	-1.377	26	0.1801
Whiting spp	0.404	0.585	0.262	1.545	4	0.1973
Invertebrates (unclassified)	-0.250	0.982	0.193	-1.299	25	0.2057
Debris	1.573	5.649	1.233	1.276	20	0.2166
Wenchman Snapper	0.284	0.453	0.203	1.401	4	0.2338
Lizardfish spp	-0.356	1.224	0.306	-1.163	15	0.2630
Fishes (unclassified)	0.728	4.037	0.692	1.052	33	0.3007
Atlantic Sharpnose	1.216	1.874	1.082	1.124	2	0.3779
Butterfish	0.326	1.306	0.494	0.660	6	0.5338
Sea Robins (small)	0.117	1.288	0.322	0.364	15	0.7212
Atlantic Croaker	0.360	7.027	1.205	0.298	33	0.7673
Longspine Porgy	0.174	4.706	0.807	0.215	33	0.8308

Table 17. Species Number (Count) CPUE *t*-test for the Georgia Cruise.

Data are presented as estimates of the mean CPUE (number of individuals/hr) difference in species number (count) CPUEs from the TTED-equipped trawl relative to the TED-equipped trawl, standard error (StdErr) around means, standard deviation (StdDev) from the mean, t-value, degrees of freedom (DF), and p-value. Significant differences of species number (count) CPUEs (p<0.05) are in bold. Atlantic Sharpnose (small) refers to neonate Atlantic Sharpnose Sharks that were kept separate from adult Atlantic Sharpnose Sharks (Atlantic Sharpnose). N/A indicates that data were unavailable due to the model not converging.

Species	**Mean**	**StdDev**	**StdErr**	**t-value**	**DF**	**p-value**
Winter Flounder	0.448	N/A	N/A	N/A	0	N/A
Blacknose Shark	0.292	0.062	0.021	14.201	8	**<0.0001**
Horseshoe Crab	1.304	0.768	0.176	7.403	18	**<0.0001**
Atlantic Sharpnose	2.027	1.638	0.321	6.308	25	**<0.0001**
Bonnethead Hammerhead	0.668	0.582	0.155	4.299	13	**0.0009**
Blacktip Shark	0.242	0.021	0.012	19.690	2	**0.0026**
Rays & Skates	0.446	0.404	0.122	3.664	10	**0.0044**
Atlantic Sharpnose (small)	4.744	7.975	1.830	2.593	18	**0.0184**
Scalloped Hammerhead	0.315	0.281	0.126	2.505	4	**0.0664**
Spanish Mackerel	0.211	0.252	0.126	1.676	3	0.1922
Smoothed Hammerhead	0.231	0.326	0.231	1.000	1	0.5000

Table 18. Species Number (Count) CPUE *t*-test for the Texas Cruise.

Data are presented as estimates of the mean CPUE (number of individuals/hr) difference in species number (count) CPUEs from the TTED-equipped trawl relative to the TED-equipped trawl, standard error (StdErr) around means, standard deviation (StdDev) from the mean, t-value, degrees of freedom (DF), and p-value. Significant differences of species number (count) CPUEs ($p<0.05$) are in bold. N/A indicates that data were unavailable due to the model not converging.

Species	Mean	StdDev	StdErr	t-value	DF	p-value
Dusky Shark	0.241	N/A	N/A	N/A	0	N/A
Spot	12.245	N/A	N/A	N/A	0	N/A
Blacknose Shark	0.197	N/A	N/A	N/A	0	N/A
Atlantic Sharpnose	0.316	0.381	0.095	3.316	15	**0.0047**
Shrimp Discard	9.116	21.441	3.270	2.788	42	**0.0079**
Southern Flounder	0.173	0.019	0.013	12.926	1	**0.0492**
Lizardfish spp	-5.169	15.542	2.838	-1.822	29	0.0789
Gulf Smouthhound	0.095	0.341	0.055	1.736	38	0.0906
Blackear Bass	163.145	270.301	90.100	1.811	8	0.1078
Butterfish	-19.960	58.067	14.083	-1.417	16	0.1756
Atlantic Angle Shark	0.187	0.273	0.122	1.530	4	0.2009
Vermillion Snapper	5.326	9.561	4.780	1.114	3	0.3464
Rock Seabass	-5.132	26.735	5.834	-0.880	20	0.3895
Lane Snapper	2.454	3.740	2.644	0.928	1	0.5238
Rough Scad	-13.325	130.938	22.456	-0.593	33	0.5570
Red Snapper	0.091	1.328	0.221	0.409	35	0.6850
Ocellated Flounder	4.368	19.487	13.779	0.317	1	0.8046
Atlantic Croaker	0.986	28.160	4.245	0.232	43	0.8175
Cutlass Fish	-2.279	18.918	9.459	-0.241	3	0.8251
Wenchman Snapper	0.673	20.776	3.132	0.215	43	0.8308
Rays & Skates	0.061	0.835	0.316	0.192	6	0.8538
Sea Robins	1.569	40.498	12.211	0.128	10	0.9003
Sea Trouts	-0.101	6.074	0.960	-0.105	39	0.9167
Longspine Porgy	-0.113	45.667	6.885	-0.016	43	0.9870

Table 19. Species Number (Count) CPUE *t*-test for the Mississippi Cruise.

Data are presented as estimates of the mean CPUE (number of individuals/hr) difference in species number (count) CPUEs from the TTED-equipped trawl relative to the TED-equipped trawl, standard error (StdErr) around means, standard deviation (StdDev) from the mean, t-value, degrees of freedom (DF), and p-value. Significant differences of species number (count) CPUEs ($p<0.05$) are in bold. Lizardfishes (small) include individuals that weighed less than 300g. Sea Robins (large) include individuals that weighed 175g or more. Sea Robins (small) includes individuals that weighed less than 175g. Crabs (large) include individuals that weighed more 200g of more. Crabs (small) includes individuals that weighed less than 200g. N/A indicates that data were unavailable due to the model not converging.

Species	Mean	StdDev	StdErr	t-value	DF	p-value
Louisiana Redfish	0.333	N/A	N/A	N/A	0	N/A
Southern Flounder	0.297	0.061	0.023	12.911	6	**<0.0001**
Sea Robins (large)	4.368	3.736	1.036	4.215	12	**0.0012**
Crabs (large)	3.751	3.702	0.956	3.924	14	**0.0015**
Rays & Skates	0.289	0.249	0.079	3.671	9	**0.0051**
Lizardfishes (large)	2.105	1.325	0.501	4.204	6	**0.0057**
Spot	-12.685	24.005	4.537	-2.796	27	**0.0094**
Gulf Smoothhound	0.327	0.128	0.064	5.125	3	**0.0144**
Spanish Mackerel	0.306	0.038	0.027	11.286	1	0.0563
Butterfish	7.619	8.624	3.259	2.337	6	0.0580
Wenchman Snapper	12.005	11.106	4.967	2.417	4	0.0730
Sea Trouts	5.640	19.909	3.414	1.652	33	0.1081
Whitings	2.142	2.379	1.064	2.013	4	0.1144
Shrimp Discard	-3.382	13.029	2.419	-1.398	28	0.1731
Red Porgy	-1.942	0.826	0.584	-3.327	1	0.1859
Red Snapper	0.243	1.304	0.261	0.931	24	0.3609
Atlantic Sharpnose	0.405	0.625	0.361	1.124	2	0.3779
Atlantic Croaker	12.015	168.481	28.894	0.416	33	0.6802
Longspine Porgy	3.559	107.493	18.435	0.193	33	0.8481

Table 20. Small Fish Weights and CPUEs by Cruise.

Data are presented as the sum of the small fish bycatch weight for all valid tows for the TED-equipped trawl (kg TED) and TTED-equipped trawl (kg TTED) by cruise. The two CPUE (kg/hr) columns refer to the small fish bycatch weight from the TED-equipped trawl (total small fish bycatch TED /total hours towed) and the TTED-equipped trawl (total small fish bycatch TTED/total hours towed). Kg diff is the difference in total small fish bycatch weight of the TED-equipped trawl relative to the TTED-equipped trawl (kg TTED minus kg TED). % diff is the percent difference in total small fish bycatch weight of the TED-equipped trawl relative to the TTED-equipped trawl.

Cruise	Kg TED	Kg TTED	CPUE TED	CPUE TTED	kg diff	% diff
GA	3541.7	2267.8	36.86	23.22	-13.64	-37.03%
TX	6929.57	6737.76	33.06	32.09	-191.81	-5.8%
MS	6189.7	5899.56	54.44	52.21	-290.14	-5.3%

Table 21. Small Fish Weight CPUE *t*-test by Cruise.

Data are presented as estimates of the mean CPUE (kg/hr) difference in small fish weight CPUEs from the TTED-equipped trawl relative to the TED-equipped trawl, standard error (StdErr) around means, standard deviation (StdDev) from the mean, t-value, degrees of freedom (DF), and p-value. Significant differences of small fish weight CPUEs (p<0.05) are in bold.

Cruise	Mean	StdDev	StdErr	t-value	DF	p-value
GA	1.274	1.406	0.256693	4.962061	29	**0.00002**
TX	0.038	0.178	0.02688	1.429313	43	0.16014
MS	0.109	0.592	0.10147	1.071552	33	0.291696

Table 22. GLMM Specifications for Shark spp. and Red Snapper Relative Capture Efficiency at Length (TTED versus TED).

Generalized linear mixed models for evaluating length (unpooled) as a predictor of capture efficiency of the TTED-equipped trawl (REtted) relative to the TED-equipped trawl. Model building results for the capture efficiency of the TTED-equipped trawl (REtted) relative to the TED-equipped trawl by species or species group and cruise combination examined in the analysis. The fixed effects included in the Model Specification column were those that resulted in the lowest AIC value for that particular species. A random station effect [bracketed] was included for every model. Species where the intercept only model did not provide estimates of relative efficiency are indicated as failed to converge.

Cruise	**Date**	**Species**	**Model Specification**
ALL		Carcharhinids grouped	REtted ~ intercept + length + tow depth + [station]
GA	Mai	Carcharhinids grouped	REtted ~ intercept + length + [station]
TX	July	Carcharhinids grouped	Did not converge
MS	August	Carcharhinids grouped	Did not converge
GA	Mai	Sharpnose Shark	REtted ~ intercept + length + [station]
TX	July	Sharpnose Shark	Did not converge
MS	August	Sharpnose Shark	REtted ~ intercept + [station]
TX	July	Gulf Smoothhound	REtted ~ intercept + tow depth [station]
MS	August	Gulf Smoothhound	Did not converge
GA	Mai	Hammerheads grouped	Did not converge
TX	July	Red Snapper	REtted ~ intercept + [station]
MS	August	Red Snapper	REtted ~ intercept + [station]

Table 23. GLMM Specifications for Relative Capture Efficiency (TTED versus TED) of Numbers of Individuals by Species.

General linear mixed model building results for the capture efficiency of the TTED-equipped trawl (REtted) relative to the TED-equipped trawl by species or species group and cruise combination examined in the analysis. The fixed effects included in the Model Specification column were those that resulted in the lowest AIC value for that particular species. A random station effect [bracketed] was included for every model. Species where the intercept only model did not provide estimates of relative efficiency are indicated as failed to converge. Sea Robins (large) include individuals that weighed 175g or more. Crabs (large) includes individuals that weighed more 200g of more.

Cruise	**Species**	***Model Specification***
ALL	Carcharhinids grouped	REtted ~ intercept + length + tow depth + [station]
GA	Carcharhinids grouped	REtted ~ intercept + length + [station]
TX	Carcharhinids grouped	Did not converge
MS	Carcharhinids grouped	Did not converge
GA	Sharpnose Shark	REtted ~ intercept + length + [station]
TX	Sharpnose Shark	Did not converge
MS	Sharpnose Shark	REtted ~ intercept + [station]
TX	Gulf Smoothhound	REtted ~ intercept + tow depth + [station]
MS	Gulf Smoothhound	Did not converge
GA	Hammerheads grouped	Did not converge
TX	Red Snapper	REtted ~ intercept + [station]
MS	Red Snapper	REtted ~ intercept + [station]

Table 24. GLMM Results Using Length (unpooled) Data From Catch.

Results are from the models that provided the best fit to the data as supported by model comparison (minimum AIC value). LCL (lower confidence limits) and UCL (upper confidence limits) are Wald type. Parameter estimates are on the logit scale and the Exp(Est) is the estimated relative efficiency of the TTED-equipped trawl relative to the TED-equipped trawl on the probability scale. Significant of length as a predictor variable of catch efficiency of the TTED-equipped trawl relative to the TED-equipped trawl (p<0.05) are in bold.

Cruise	**Species**	**Effect**	**Estimate**	**StdErr**	**DF**	**t-value**	**p-value**	**LCI**	**UCI**	**Exp(Est)**
ALL	Carcharhinids	Intercept	2.6753	0.7480	47	3.58	**0.0008**	1.1705	4.1802	14.5167
		Length	-0.0133	0.0030	73	-4.46	<0.0001	-0.1931	-0.0074	0.9867
		Tow Depth	0.0577	0.0211	73	2.73	0.0079	0.0156	0.0998	1.0594
GA	Carcharhinids	Intercept	4.0675	1.6242	27	2.5	**0.0186**	0.7349	7.4001	58.4108
		Length	-0.0171	0.0059	55	-2.89	0.0055	0.0051	0.0290	0.9831
GA	Atlantic sharpnose	Intercept	3.3188	1.2180	26	2.71	**0.0114**	0.8152	5.8225	27.6272
		Length	-0.0143	0.0044	39	-3.25	0.0024	-0.0232	-0.0054	0.9858
TX	Gulf Smoothhound	Intercept	2.4493	1.5476	36	1.58	0.1223	-0.6894	5.5879	0.7271
		Tow Depth	-0.0501	0.0277	63	-1.81	0.0749	-0.1054	0.0052	0.9511

Table 25. Generalized Linear Mixed Model for Lizardfishes.

Estimating the capture efficiency of TTED-equipped (REtted) trawl relative to the TED-equipped trawl using the pooled (count) catch data. Results are from the model that provided the best fit (intercept and tow depth) to the data as supported by model comparison (minimum AIC value), with Wald type confidence intervals. Parameter estimates are on the logit scale and the exp(Estimate) is the estimated relative efficiency on the probability scale. Percent change represents the average percentage change in the catch of TTED-Equipped Trawl Relative to the TED-Equipped Trawl. Significant ($p<0.05$) of catch efficiency are in bold.

Cruise	**Date**	**Species**	**Model Specification**	**Estimate**	**SE**	**DF**	**t-value**	**p-value**	**LCI**	**UCI**	**Exp(Est)**	**% Change**
TX	July	Lizardfishes	Intercept	-1.5253	4.1465	28	-2.78	**0.0096**	-20.0190	-3.0315	1.977E-11	-100
			Tow depth	0.2376	0.0764	28	3.11	0.0043	0.0812	0.3941	1.2682	
MS	August	Spot	Intercept	0.0310	0.0209	32	1.49	0.1467	-0.0115	0.0735	0.97301	-2.70
			Total bycatch reduction (kg)	0.0024	0.0005	32	4.91	<0.0001	0.0014	0.0035	1.0024	

Table 26. GLMM Results Using Count (unpooled) Data From Catch (intercept only model).

Estimating the capture efficiency of TTED-equipped (REtted) trawl relative to the TED-equipped trawl using the pooled (count) catch data. Results are from the model that provided the best fit (intercept only) to the data as supported by model comparison (minimum AIC value), with Wald type confidence intervals. Parameter estimates are on the logit scale and the exp(Estimate) is the estimated relative efficiency on the probability scale. Percent change represents the average percentage change in the catch of TTED-Equipped Trawl Relative to the TED-Equipped Trawl. Significant ($p<0.05$) of catch efficiency are in bold.

Cruise	Species	Model Specification	Estimate	SE	DF	t-value	p-value	LCI	UCI	Exp(Est)	% Change
TX	Red snapper	REtted ~ intercept + [station]	-0.0082	0.1243	35	-0.07	0.9479	-0.2605	0.2442	0.9919	-0.81
MS	Red Snapper	REtted ~ intercept + [station]	-0.1145	0.2187	24	-0.52	0.6055	-0.5659	0.3369	0.8918	-10.82
MS	Sea Robins (large)	REtted ~ intercept + [station]	-5.2576	1.9487	12	-2.7	**0.0194**	-9.5056	-1.0117	0.0052	-99.48
TX	Atlantic Croaker	REtted ~ intercept + [station]	-0.0866	0.0970	43	0.89	0.3769	-1090.0	0.2823	0.9170	-8.30
MS	Atlantic Croaker	REtted ~ intercept + [station]	-0.0292	0.0493	33	-0.59	0.5582	-0.1294	0.0711	0.9713	-2.87
TX	Longspine	REtted ~ intercept + [station]	0.0826	0.0464	43	1.78	0.0821	-0.0110	0.1762	1.0861	8.61
MS	Longspine	REtted ~ intercept + [station]	0.1057	0.0726	33	1.46	0.1547	-0.0419	0.2534	1.1115	11.15
TX	Butterfish	REtted ~ intercept + [station]	0.2708	0.7196	16	0.38	0.7116	-1.2547	1.7963	1.3110	31.10
MS	Butterfish	REtted ~ intercept + [station]	-1.3006	1.4542	6	-0.9	0.405	-4.8542	2.2530	0.2724	-72.76
TX	Sea Robin	REtted ~ intercept + [station]	1.7379	4.2258	10	0.41	0.6896	-7.6778	11.1536	5.6854	468.54
TX	Rock Seabass	REtted ~ intercept + [station]	1.3140	1.2206	20	1.08	0.2945	-1.2322	3.8601	3.7210	272.10
TX	Wenchman Snapper	REtted ~ intercept + [station]	-0.0187	0.0757	43	-0.25	0.8056	-0.1714	0.1339	0.9814	-1.86
MS	Wenchman Snapper	REtted ~ intercept + [station]	-0.4999	0.2107	4	-2.37	0.0766	-1.0848	0.0851	0.6066	-39.34
TX	Sea Trouts	REtted ~ intercept + [station]	-0.4194	0.1899	39	-2.21	**0.0332**	-0.9035	-0.0352	0.6574	-34.26
MS	Sea Trouts	REtted ~ intercept + [station]	-0.2050	0.1926	33	-1.06	0.2948	-0.5969	0.1868	0.8146	-18.54
MS	Crab (large)	REtted ~ intercept + [station]	-3.1846	0.9157	14	-3.48	**0.0037**	-5.1486	-1.2206	0.0414	-95.86

Table 27. GLM Results Using Count (unpooled) Data From Catch (intercept only model). (page 102)

General Linear Models (GLM) were used when General Linear Mixed Models did not provide results, GLM were used the Pooled (Count) Catch Data to Estimate the Capture Efficiency of TTED-Equipped Trawl Relative to the TED-Equipped Trawl. Results are for from the model that provided the best fit (intercept only) to the data as supported by model comparison (minimum AIC value). Confidence limits are Wald type confidence intervals. Parameter estimates are on the logit scale and the exp(Estimate) is the estimated relative efficiency on the probability scale. Percent change represents the average percentage change in the catch of TTED-Equipped Trawl Relative to the TED-Equipped Trawl. Significance of difference of catch efficiency of the TTED-equipped trawl relative to the TED-equipped trawl ($p<0.05$) are in bold. Lizardfishes spp (large) includes individuals that weighed 300g or more.

Cruise	Date	Species	Model Specification	Estimate	SE	DF	t-value	p-value	LCI	UCI	Exp(Est)	% Change
TX	July	**Atlantic Sharpnose Shark**	REtted ~ intercept	-2.2336	0.6075	15	-3.68	**0.0022**	-3.5284	-0.9388	0.1071	-89.29
MS	August	Atlantic Sharpnose Shark	REtted ~ intercept	-1.6094	1.0954	2	-1.47	0.2795	-6.3227	3.1039	0.2000	-80.00
GA	May	Blacknose Shark	REtted ~ intercept	-2.3026	1.0488	8	-2.2	0.0594	-4.7211	0.1160	0.1000	-90.00
GA	May	Blacktip Shark	REtted ~ intercept	-13.8445	585.770	2	-0.02	0.9833	-2534.210	2506.52	0.0000	-100.00
TX	July	Blacknose Shark	Did not converge								1.0000	0.00
TX	July	Dusky Shark	Did not converge									-100.00
TX	July	Gulfsmouthound	REtted ~ intercept	-0.3659	0.1985	38	-1.84	0.073	-0.7677	0.0358	0.6936	-30.64
MS	August	Gulfsmouthound	REtted ~ intercept	-1.7918	1.0801	3	-1.66	0.1957	-5.2292	1.6457	0.1667	-83.33
GA	May	Scaloped hammerhead	REtted ~ intercept	-1.7918	1.0801	4	-1.66	0.1725	0.0500	-4.7907	0.1667	-83.33
GA	May	Bonnethead Hammerhead	REtted ~ intercept	-3.4012	1.0165	13	-3.35	**0.0053**	-5.5973	-1.2051	0.0333	-96.67
MS	August	Smoothed Hammerhead	REtted ~ intercept	-0.6931	1.2247	1	-0.57	0.6721	-16.2550	14.8687	0.5000	-50.00
MS	August	Lizardfishes (large)	REtted ~ intercept	-16.6532	537.980	6	-0.03	0.9763	-1333.030	1299.730	0.0000	-100.00
GA	May	Rays and skates	REtted ~ intercept	-2.7081	1.0328	10	-2.62	**0.0255**	-5.0093	-0.4068	0.0667	-93.33
TX	July	Rays and skates	REtted ~ intercept	-0.4595	0.3687	11	-1.25	0.2386	-1.2711	0.3520	0.6316	-36.84
MS	August	Rays and skates	REtted ~ intercept	-1.7918	0.7638	9	-2.35	**0.0436**	-3.5195	0.0640	0.1667	-83.33
MS	August	Southern Flounder	REtted ~ intercept	-2.0795	1.0607	6	-1.96	0.0976	-4.6748	0.5159	0.1250	-87.50
GA	May	Spanish Mackerel	REtted ~ intercept	-0.6931	0.8660	3	-0.8	0.482	3.4492	2.0629	0.5000	-50.00
MS	July	Spanish Mackerel	REtted ~ intercept	-12.4588	358.830	1	-0.03	0.9779	-4571.83	4546.910	0.0000	-100.00
TX	July	Blackear bass	REtted ~ intercept	-1.2211	0.0198	8	-61.56	**<0.0001**	-1.2668	-1.1753	0.2949	-70.51
TX	July	Spot	Did not converge									
TX	July	Southern Flounder	REtted ~ intercept	-12.4588	358.830	1	-0.03	0.9779	-4571.83	4546.910	0.0000	-100.00
TX	July	Red Porgy	REtted ~ intercept	15.1218	513.570	1	0.03	0.9813	-6510.420	6540.660	3692447.2	100
TX	July	Ocellated Flounder	REtted ~ intercept	-1.0207	0.1844	1	-5.53	0.1138	-3.3639	1.3226	0.3603	-81.56
TX	July	Lane Snapper	REtted ~ intercept	-1.2528	0.3560	1	-3.49	0.1775	-5.8088	3.3033	0.2857	-64.40
TX	July	Vermillion snapper	REtted ~ intercept	-0.3278	0.0759	3	-4.32	**0.0228**	-5692.000	0.0864	0.7205	-27.95
MS	August	Whiting spp	REtted ~ intercept	-1.5163	0.3681	4	-4	**0.0146**	-2.5384	-0.4943	0.2195	-78.05

Table 28. GLM Results for Shrimp Catch Weight for All Cruises.

Generalized linear mixed model results for estimating the capture efficiency of TTED-equipped (REtted) trawl relative to the TED-equipped trawl using shrimp weight catch data. Results are from the model that provided the best fit (intercept and tow depth) to the data as supported by model comparison (minimum AIC value), with Wald type confidence intervals. Parameter estimates are on the logit scale and the exp(Estimate) is the estimated relative efficiency on the probability scale. Percent change represents the average percentage change in the catch of TTED-Equipped Trawl Relative to the TED-Equipped Trawl. Significant ($p<0.05$) of catch efficiency are in bold.

Cruise	**Species**	**Model Specification**	**Estimate**	**SE**	**DF**	**t-value**	**p-value**	**LCI**	**UCI**	**Exp(Est)**	**% Change**
GA	White Shrimp	Intercept	-0.0385	0.0488	30	-0.79	**0.4369**	-0.1381	0.0612	0.9623	-3.77
TX	Brown Shrimp	Intercept	0.0594	0.0261	42	2.28	**0.0277**	0.0068	0.1120	1.052988592	5.30
		Total bycatch reduction (kg)	0.0015	0.0008	42	1.91	0.063	-0.0001	0.0032	1.0015	
MS	Brown Shrimp	Intercept	0.0231	0.0420	32	0.55	0.5852	-0.0623	0.1086	0.987382781	-1.26
		Total bycatch reduction (kg)	0.0015	0.0010	32	1.52	0.1372	-0.0005	0.0035	1.0015	

Table 29. Catches of Rare Species.

Model specifications and number of animals caught in the TED-equipped trawl and TTED-equipped trawl and percent change in number (count) for species that were not frequently encountered in the catch.

Cruise	Species	Model Specification and occurence of 'rare' animals	% Change
TX	**Atlantic sharpnose**	28 in TED 3 in TTED	-89.29
MS	Atlantic sharpnose	REtted ~ intercept * 5 in TED 1 in TTED	-80.00
GA	Blacknose Shark	REtted ~ intercept * 11 in TED versus 1 in TTED	-90.00
GA	Blacktip Shark	REtted ~ intercept * 3 in TED side	-100.00
TX	Blacknose Shark	Did not converge * only one animal caught on TED side	0.00
TX	Dusky Shark	Did not converge * only one animal caught on TED side	-100.00
TX	Gulfsmouthound	REtted ~ intercept * 5 in TED 1 in TTED	-30.64
MS	Gulfsmouthound	Retted ~ intercept * 6 in TED 1 in TTED	-83.33
GA	Scaloped hammerhead	REtted ~ intercept * 6 in TED versus 1 in TTED	-83.33
GA	Bonnethead Hammerhead	REtted ~ intercept * 30 in TED versus 1 in TTED	-96.67
MS	Smoothed Hammerhead	REtted ~ intercept * 2 on TED versus 1 on TTED	-50.00
MS	Large Lizardfishes	REtted ~ intercept * a few observations with 0's	-100.00
GA	Rays and skates	Retted ~ intercept * 15 in TED versus 1 in TTED	-93.33
TX	Rays and skates	REtted ~ intercept * 14 in TED 11 in TTED	-36.84
MS	Rays and skates	Retted ~ intercept * 12 in TED 2 in TTED	-83.33
MS	Southern Flounder	REtted ~ intercept * 10 in TED versus 1 in TTED	-87.50
GA	Spanish Mackerel	Retted ~ intercept * 4 versus 2 animals	-50.00
MS	Spanish Mackerel	Retted ~ intercept * 2 versus 0 animals	-100.00
TX	Blackear bass *	REtted ~ intercept * a few observations with 0's	-70.51
TX	Spot	Did not converge * 1 observation	
TX	Southern Flounder	Retted ~ intercept * 2 versus 0 animals	-100.00
TX	Red Porgy	REtted ~ intercept * 2 observations for TTED side only (14 fish)	100.00

Table 30. Summary of 2013 Sampling Cruises.
Dates, days at sea, locations, target species for the Gulf of Mexico (GOM) offshore cruise.

Location & Species	**Dates**	**Days-at-Sea**	**ValidTows**
Northern GOM (Mississippi—Louisiana) • Brown *Farfantepenaeus aztecus*	Sept 23-Oct 27	21	20
SE GOM (Florida)	Nov 4-Dec 9	36	
• Pink *Farfantepenaeus duorarum*			29
• Royal Red *Hymenoppenaeus robustus*			10
Northern GOM (Alabama)			
• White *Litopenaeus setiferus*			8
TOTAL		57	67

Table 31. Summary of 2013 Field Observations: TTED v. TED Catch Performance. Qualitative comparison of species encountered during comparative towing experiments.

ELASMOBRANCH	**Bycatch Reduction Performance**	**Comments**
Atlantic Sharpnose	**TTED** > TED	+100 individuals caught with TED
Bonnethead Shark	**TTED** > TED	
Gulf Smoothhounds	**TTED** > TED	20 ind. caught by TED
Butterfly rays	**TTED** > TED	7 ind. caught with TED
Raja spp.	**TTED** > TED	Noticeable difference
FISHES		
Snapper (small) < 25cm	**TTED = TED**	No noticeable difference
Snapper (large) > 30cm	**TTED** > TED	Noticeable difference
Cobia (large) 60-80cm	**TTED** > TED	3 ind. Caught with TED
Hognose Wrasse (large) > 30cm	**TTED** > TED	
Gaffltop Catfish	**TTED** > TED	Noticeable difference
Sea Robins	**TTED** > TED	Larger ind. caught by TED
Lizardfishes	**TTED** > TED	Larger ind. caught by TED
King Mackerel	**TTED** > TED	Not frequent but noticeable
INVERTEBRATES		
Rooster Crab (large	**TTED** > TED	Noticeable difference
blue crabs spp (large)	**TTED** > TED	Noticeable difference Northern GOM
Slipper Lobster (large)	**TTED** > TED	150 caught in TED versus O in TTED in Northern GOM
Slipper lobsters (small)	**TTED** > TED	Less in TTED the TED but still present in TTED
Sponges	**TTED** > TED	Drastic difference in SE GOM
JELLYFISH		
Moon jellyfish	**TTED** > TED	Drastic difference in SE GOM
SHRIMP	**Target Species Catch**	
Brown Shrimp	**TTED = TED**	Sub-sample showed 0.8% less shrimp with TTED
Pink Shrimp	**TTED > TED**	Increase production with jellyfish present
Royal Red Shrimp	**TTED = TED**	No difference in catch measured
White Shrimp	**TTED = TED**	No difference in catch measured

FIGURES

Figure 1. Gulf of Mexico Offshore Shrimp Trawling Effort and Landings (1960-2011).
Total days fished (24 hour days) per year and total shrimp production (MT of shrimp tails) in the Gulf of Mexico. Data provided by NOAA Galveston Lab.

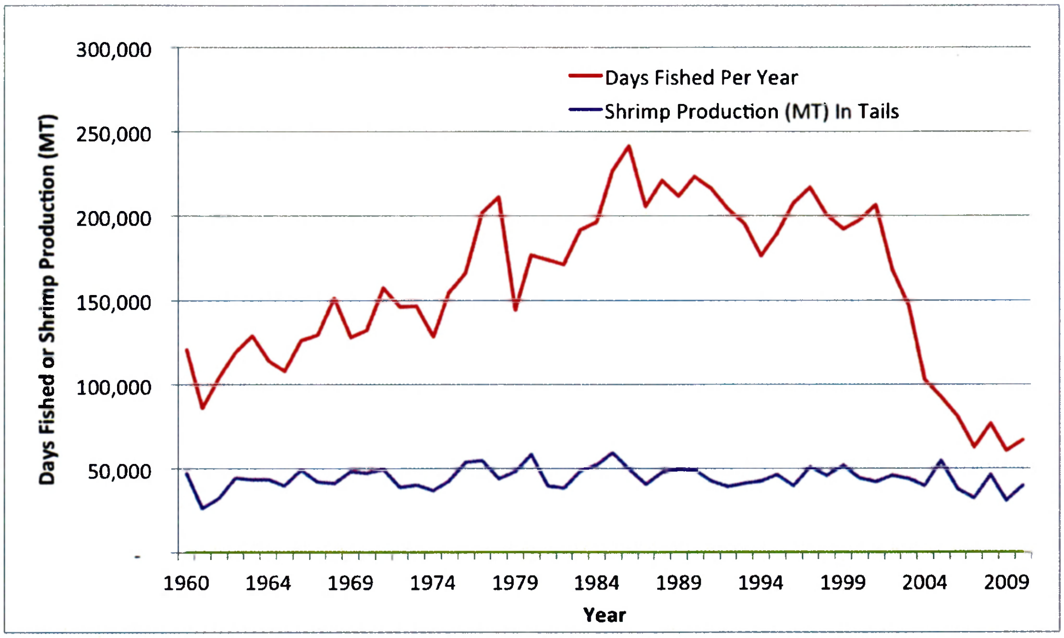


Figure 2. Gulf of Mexico Offshore Shrimp Trawling CPUE (1960-2011).
CPUE measured as MT of shrimp tails per day fished (24 hour day). Data provided by NOAA Galveston Lab.

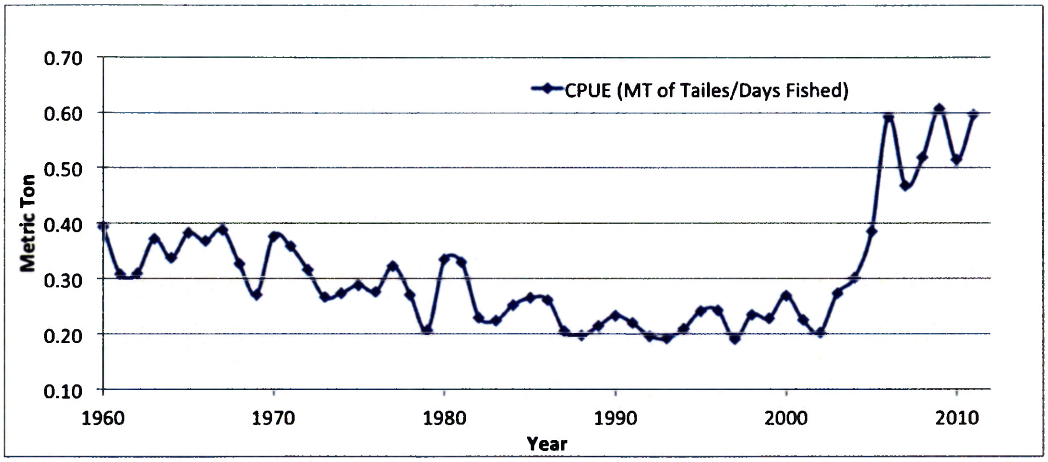


Figure 3. Typical Gear Configurations for Vessels Participating in the Southeastern Offshore Shrimp Fishery.

This drawing depicts a shrimp vessel equipped with quad trawls (two pairs of twin-trawls). From Scott-Denton et al. (2012).

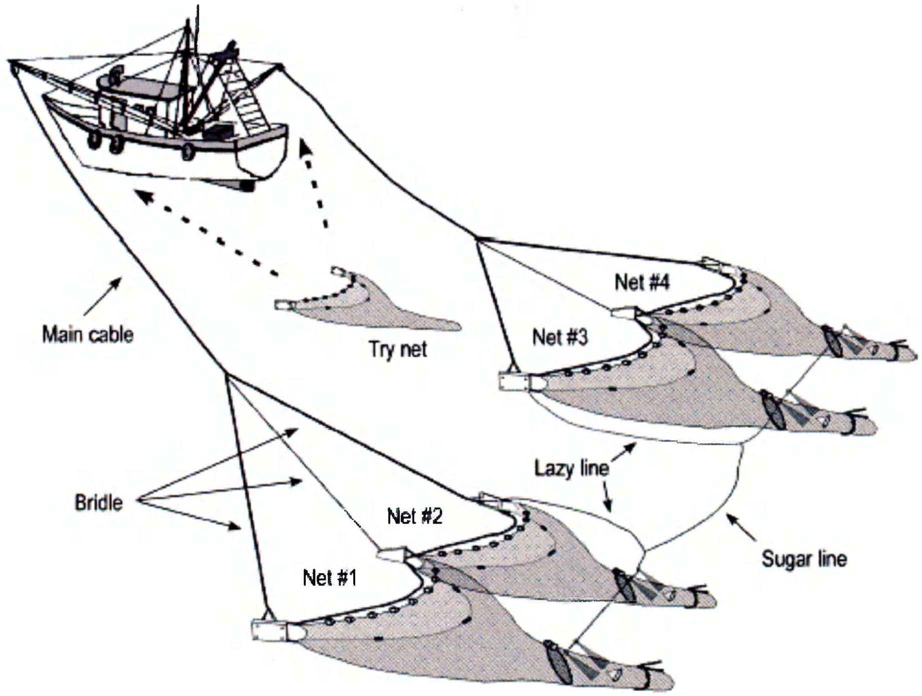


Figure 4. Catch and Bycatch Composition of the Gulf of Mexico Offshore Shrimp Fishery. Catch and bycatch composition as reported by Scott-Denton et al. (2012) for the years 2007-2010.

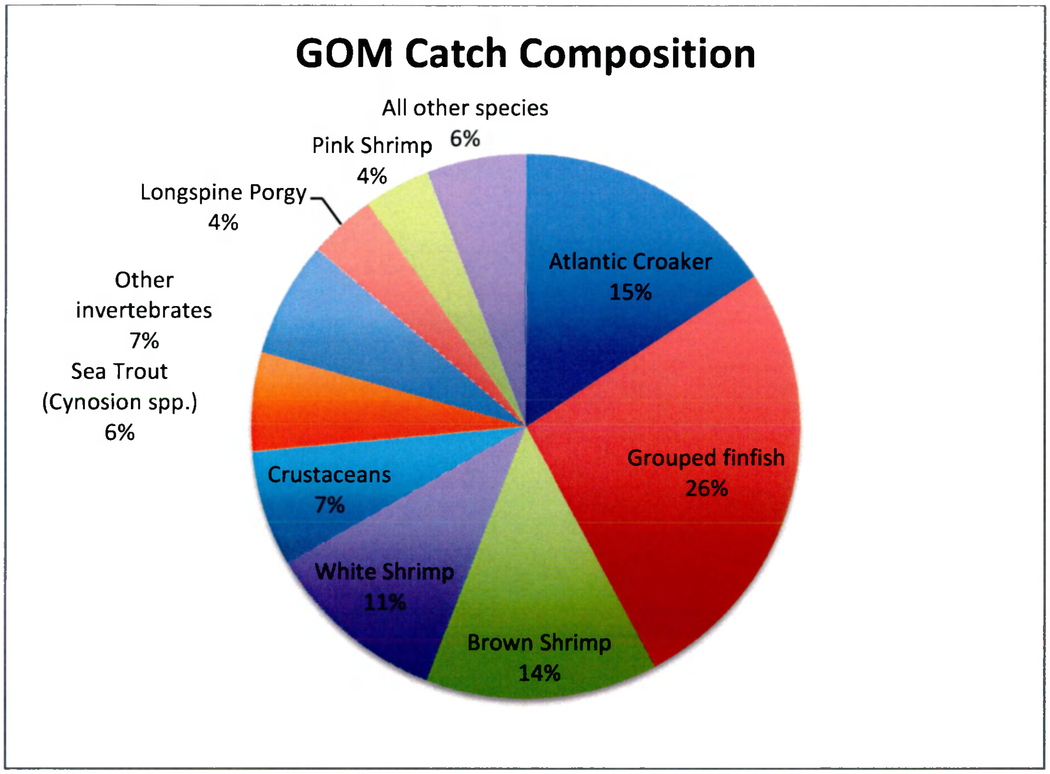


Figure 5. Typical Flat Net Trawl Gear Configuration for a Gulf of Mexico Shrimp Trawler. Top: Configuration of a single trawl, Bottom: Configuration of a single twin-trawl. From: Scott-Denton et al. (2012).

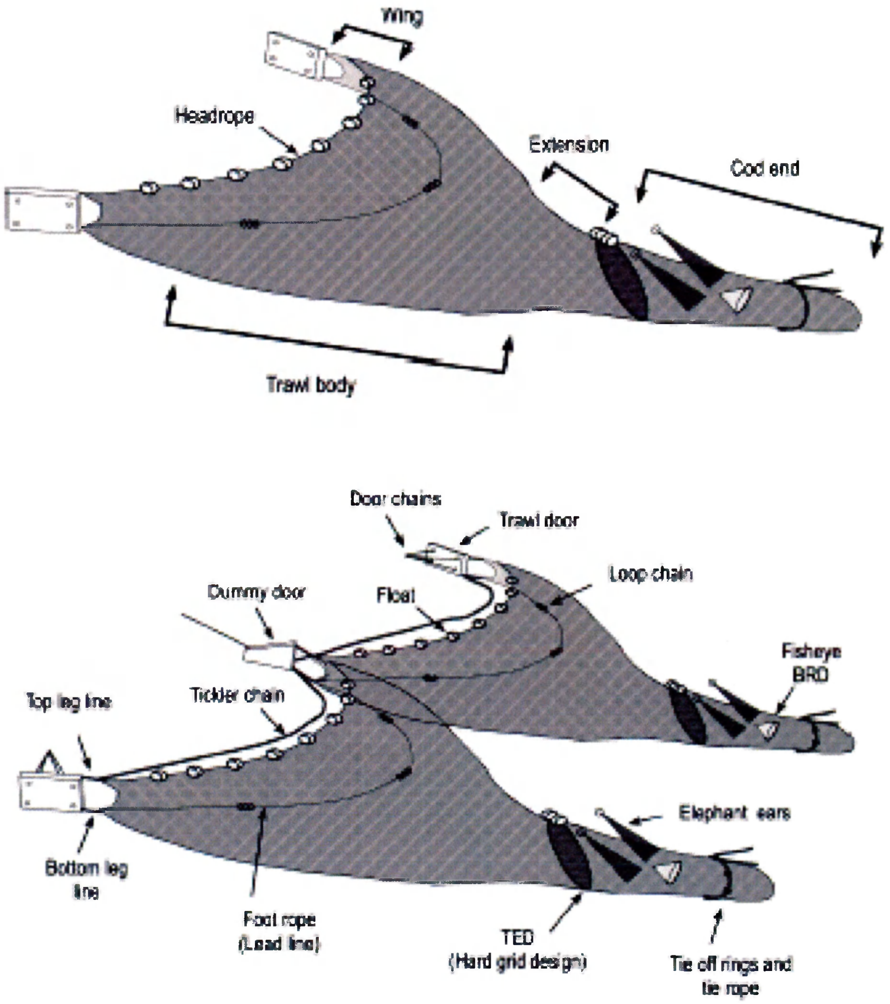


Figure 6. Diagram of a Turtle Excluder Device (TED).
The TED consists of a metal separator grid that is installed in the trawl at an inclined angle. This particular TED has an accelerator funnel installed ahead of the TED grid. Image: NOAA Internet database.

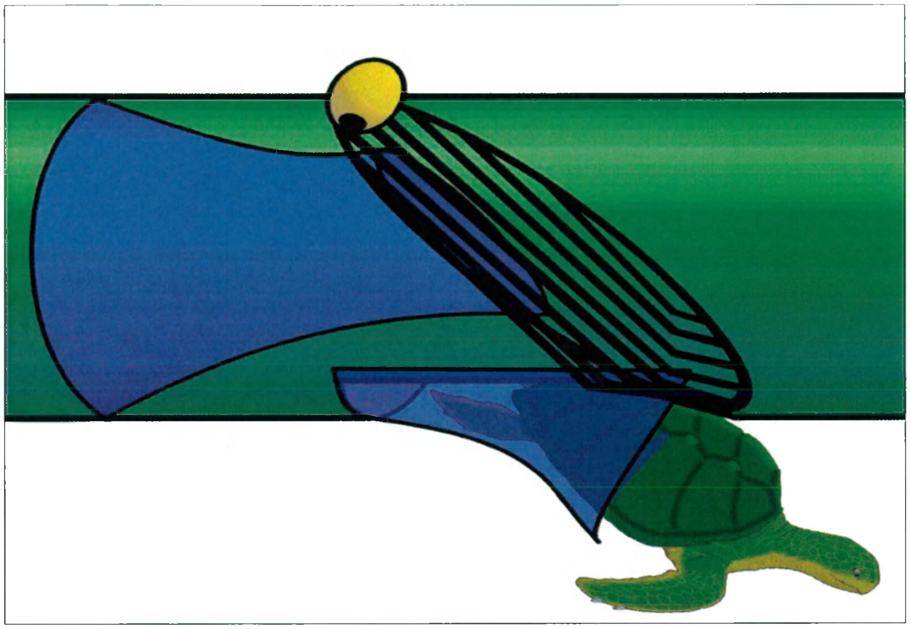


Figure 7. Profile View of Super-Shooter TED Grid.

This is side view of the TED super-Shooter Grid at 45° of inclination. In this case the front of the trawl would be to the left and the codend to the right. Refer to fig. 8 for front view. Image: NOAA Internet database.

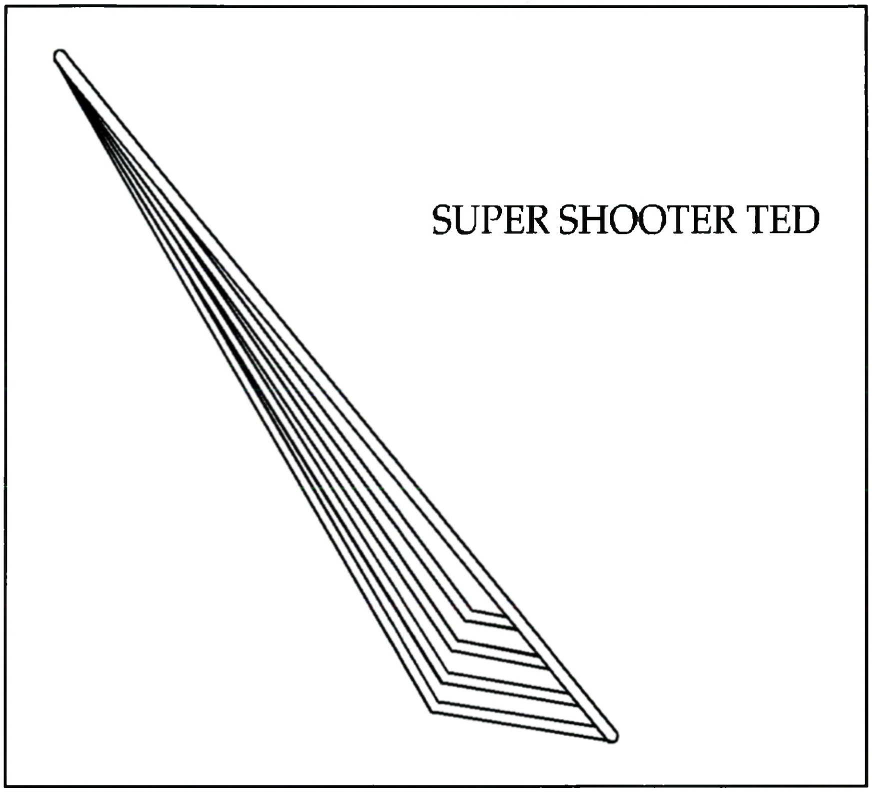


Figure 8. Trash and Turtle Excluder Device (TTED) Front View.
This is a front view of the TTED. The aluminum pipe of the frame (A) has an inside diameter of 2.54cm while the outside diameter of the pipe is 3.5cm There is 5cm of spacing between the bars (B). The flat bars of the grid (C) have 6.3mm in width and 3.8cm in depth. The structural support pipe (D) has the same diameter as the frame. The height and width of the frame are 130cm and 107cm, respectively. For a side view of the TTED see fig. 7. Image: NOAA Internet database.

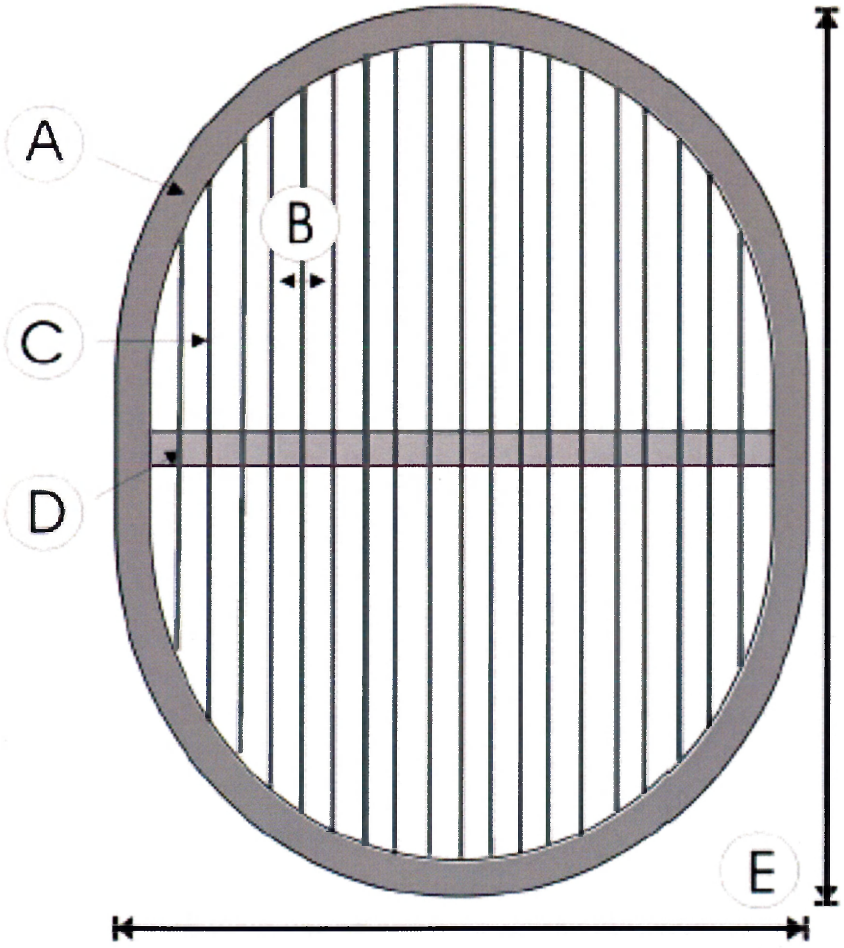


Figure 9. 2012 Gear Comparisons Sampling Stations of the Southeast Atlantic Bight and Gulf of Mexico.

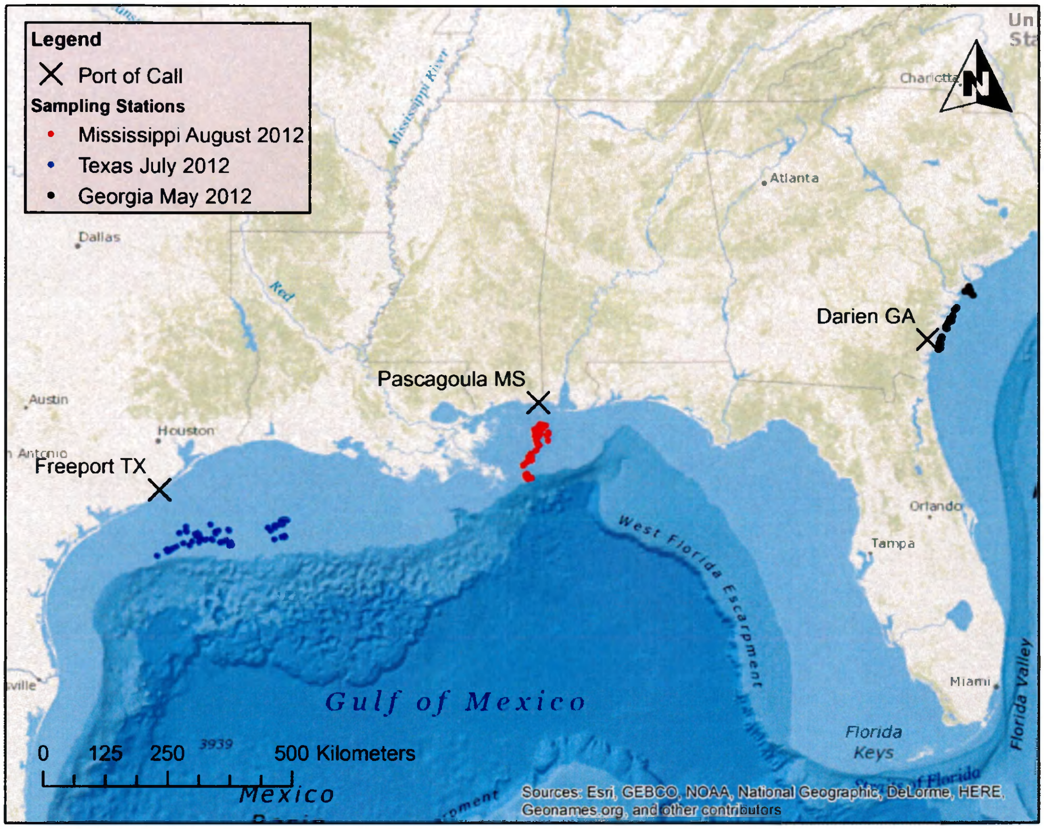


Figure 10. Relative Carcharhinid Catch at Length in the TTED versus TED (All Trips Combined).
The triangles represent the observed proportion at length (Catch TTED/(CatchTTED + CatchTED), with a proportion <0.5 representing more animals at length captured by the TED-equipped trawl. The solid black line represents the modeled predicted proportion of carcharhinid sharks at length that would be captured by the TTED-equipped trawl relative to the TED-equipped trawl.

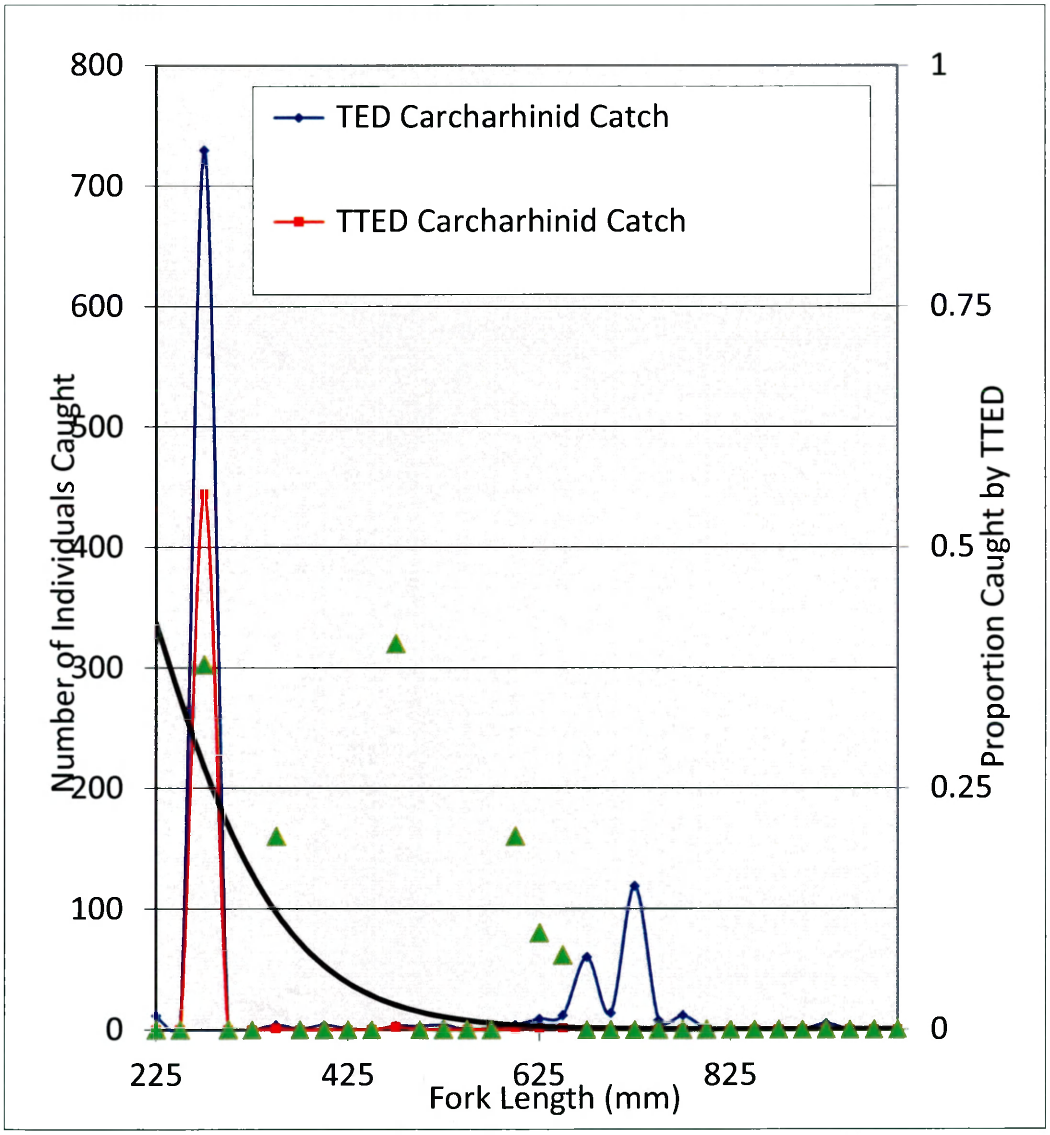


Figure 11 Relative Gulf Smoothhound Catch at Length in the TTED versus TED (All Trips Combined).

The triangles represent the observed proportion at length (Catch TTED/(CatchTTED + CatchTED), with a proportion <0.5 representing more animals at length captured by the TED-equipped trawl. For this species, the model determined that length was not a significant predictor of catch efficiency by the TTED-equipped trawl relative to the TED-equipped trawl.

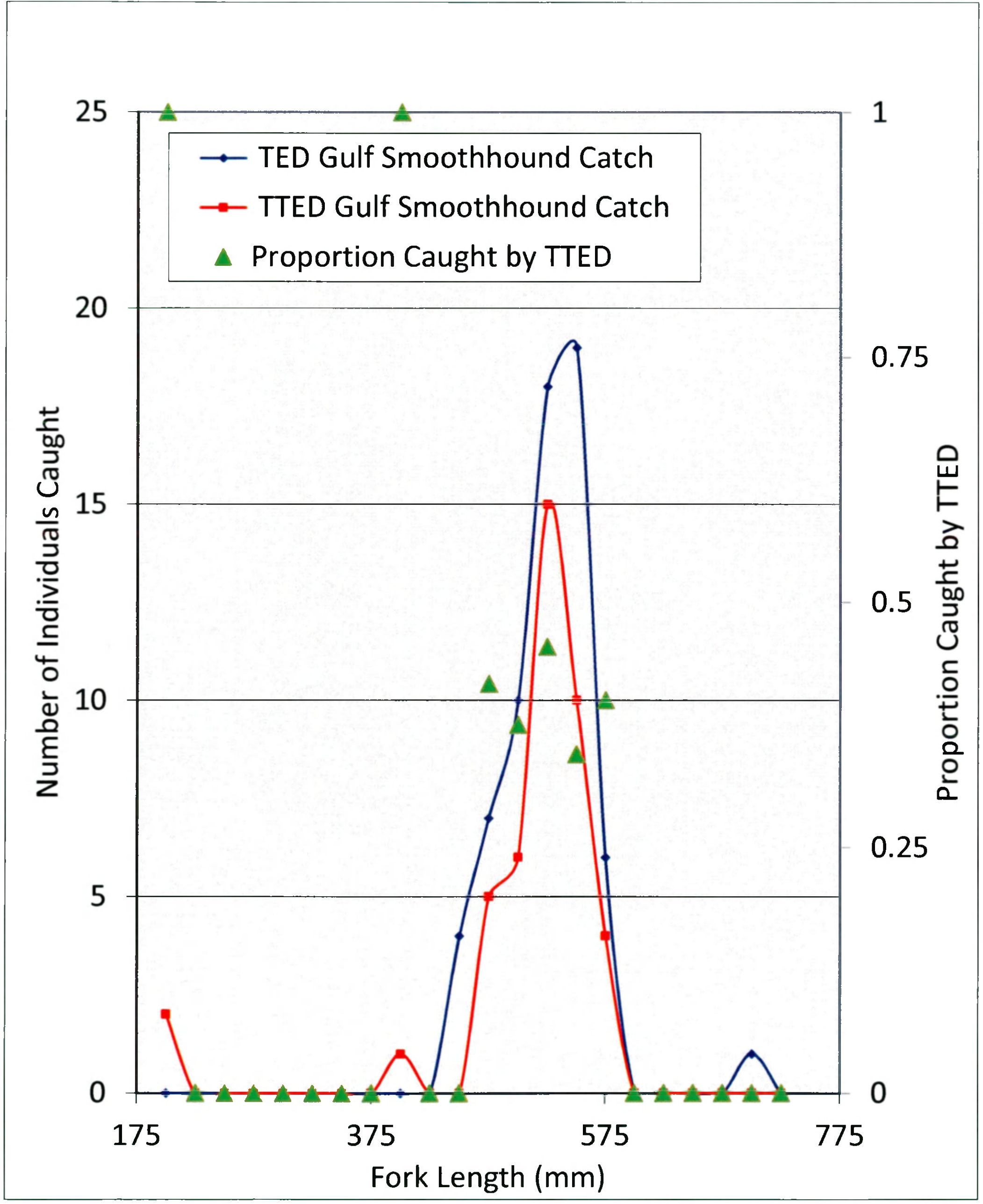


Figure 12. TX Lizardfishes Relative Capture Efficiency (TTED versus TED). Results from the 2012 Texas cruise. Analysis of the pooled data indicated that the intercept and tow depth model was the most appropriate. The estimated relative efficiency for lizardfishes (Synodontidea) is shown as the blue line. The gray line has a slope of one to simulate equal relative efficiency of the TTED-equipped trawl relative to the TED-equipped trawl.

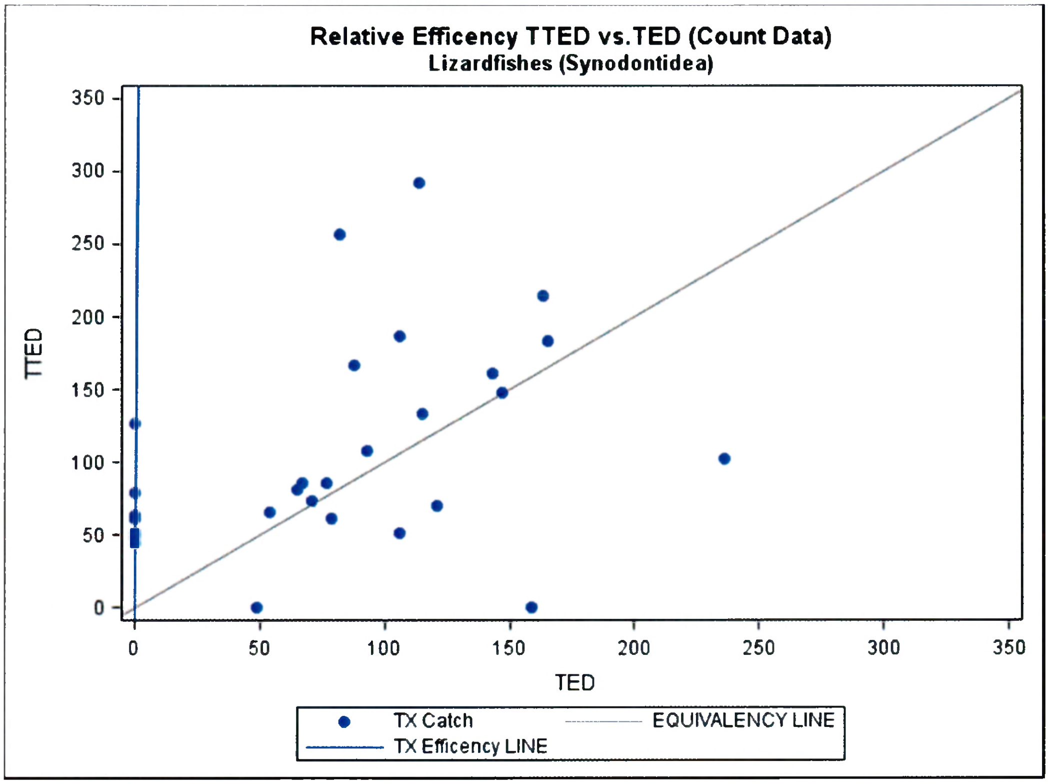


Figure 13. MS Large Sea Robins Relative Capture Efficiency (TTED versus TED).
Results from the 2012 Mississippi cruise. Analysis of the pooled data indicated that the intercept only model was the most appropriate. The estimated relative efficiency for large sea robins (Triglidae) is shown as the blue line. The gray line has a slope of one to simulate equal relative efficiency of the TTED-equipped trawl relative to the TED-equipped trawl.

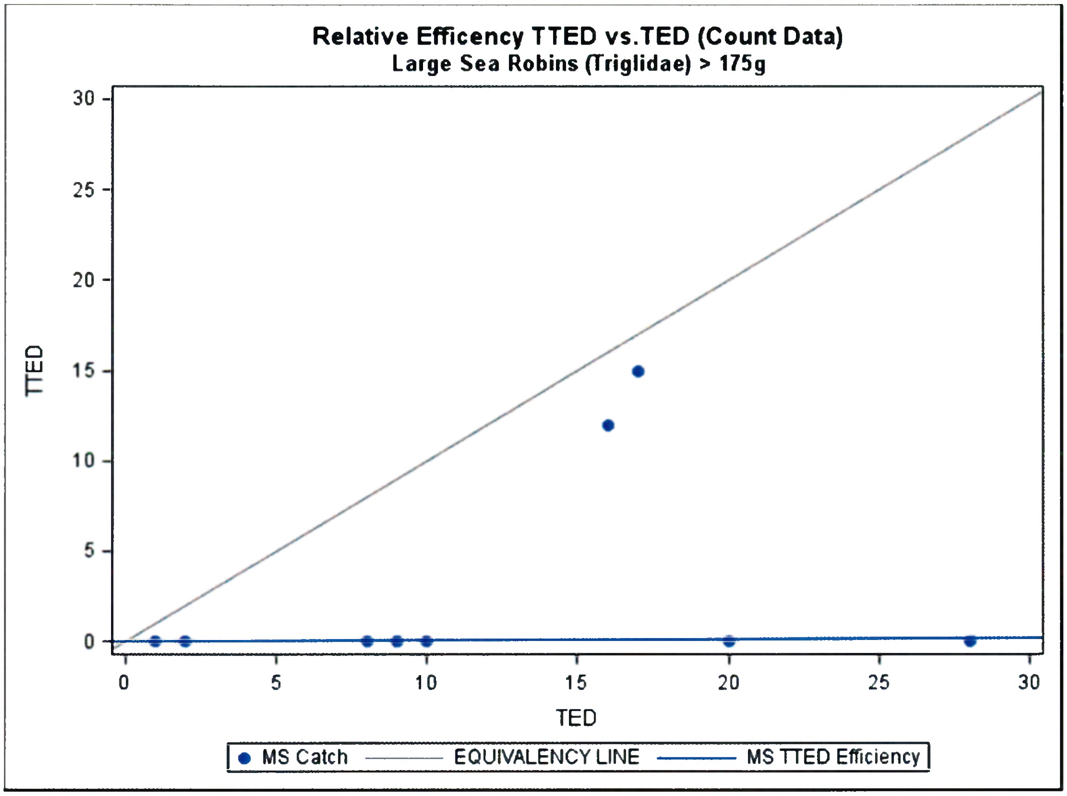


Figure 14. TX Large Sea Trouts Relative Capture Efficiency (TTED versus TED). Results from the 2012 Texas cruise. Analysis of the pooled data indicated that the intercept only model was the most appropriate. The estimated relative efficiency for sea trouts (Cynoscion spp.) is shown as the blue line. The gray line has a slope of one to simulate equal relative efficiency of the TTED-equipped trawl relative to the TED-equipped trawl.

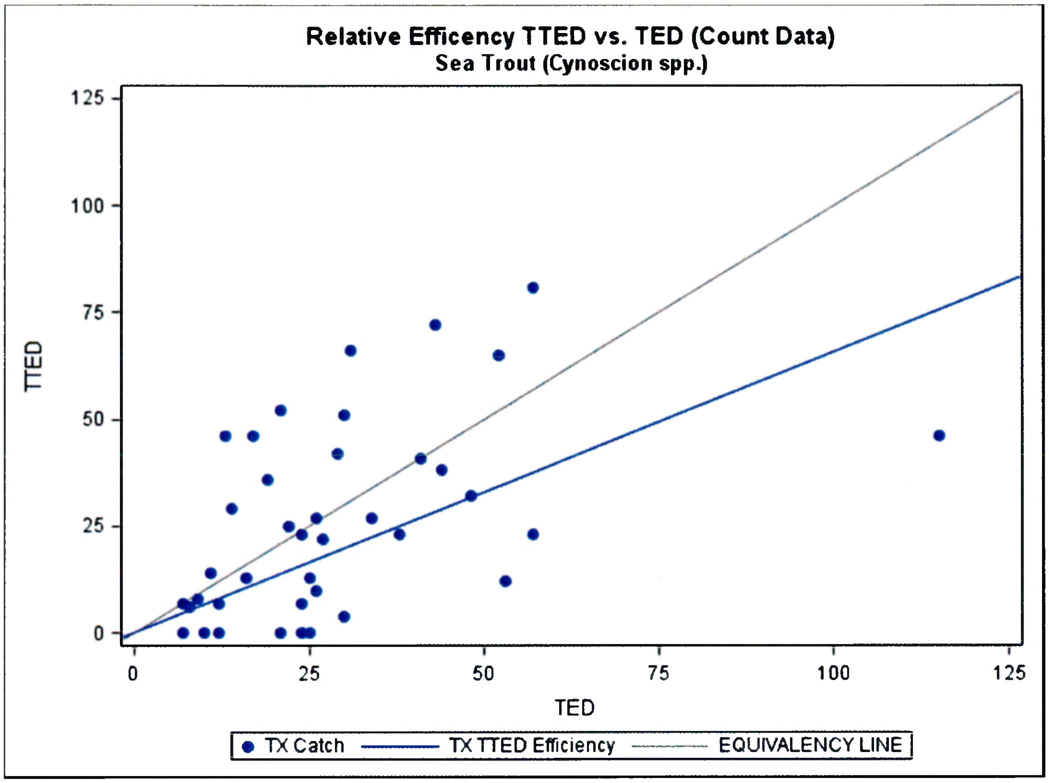


Figure 15. MS Large Crabs (Rooster Crab and Blue Crab species) Relative Capture Efficiency (TTED versus TED).

Results from the 2012 Mississippi cruise. Analysis of the pooled data indicated that the intercept only model was the most appropriate. The estimated relative efficiency for large crab (Rooster Crab and blue crab spp.) is shown as the blue line. The gray line has a slope of one to simulate equal relative efficiency of the TTED-equipped trawl relative to the TED-equipped trawl.

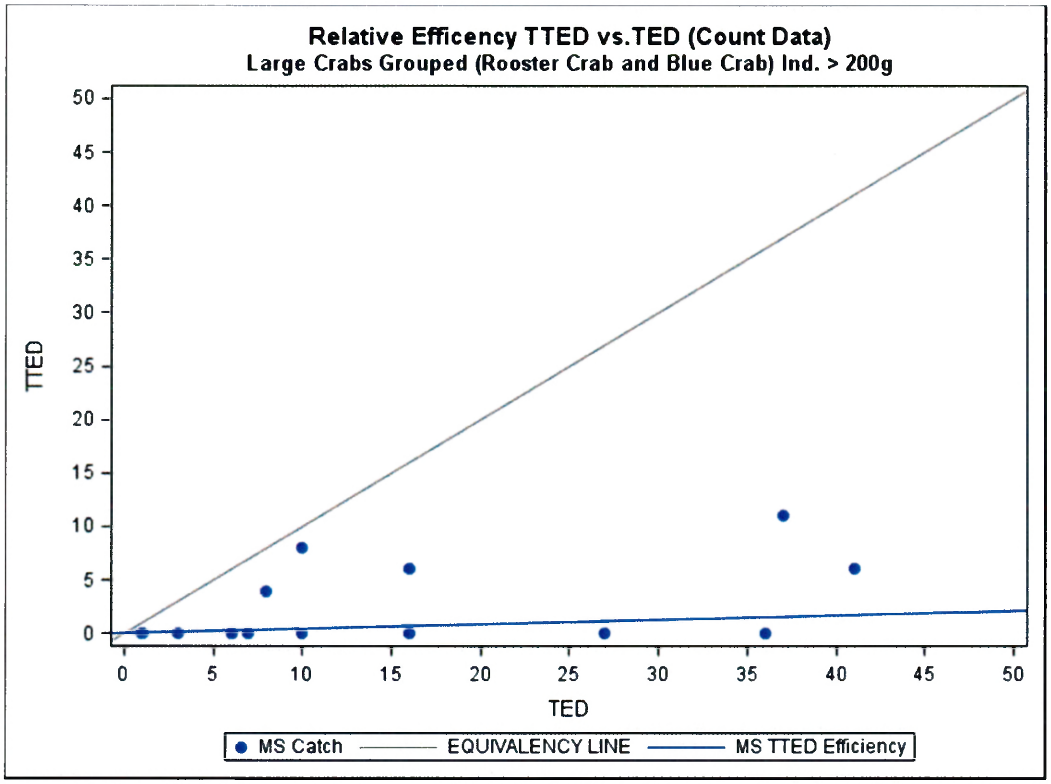


Figure 16. TX and MS Atlantic Sharpnose Shark Relative Capture Efficiency (TTED versus TED). Results from the 2012 Texas and Mississippi cruises. Analysis of the pooled data indicated that the intercept only model was the most appropriate. The estimated relative efficiency for Atlantic Sharpnose Shark is shown as the blue line. The gray line has a slope of one to simulate equal relative efficiency of the TTED-equipped trawl relative to the TED-equipped trawl.

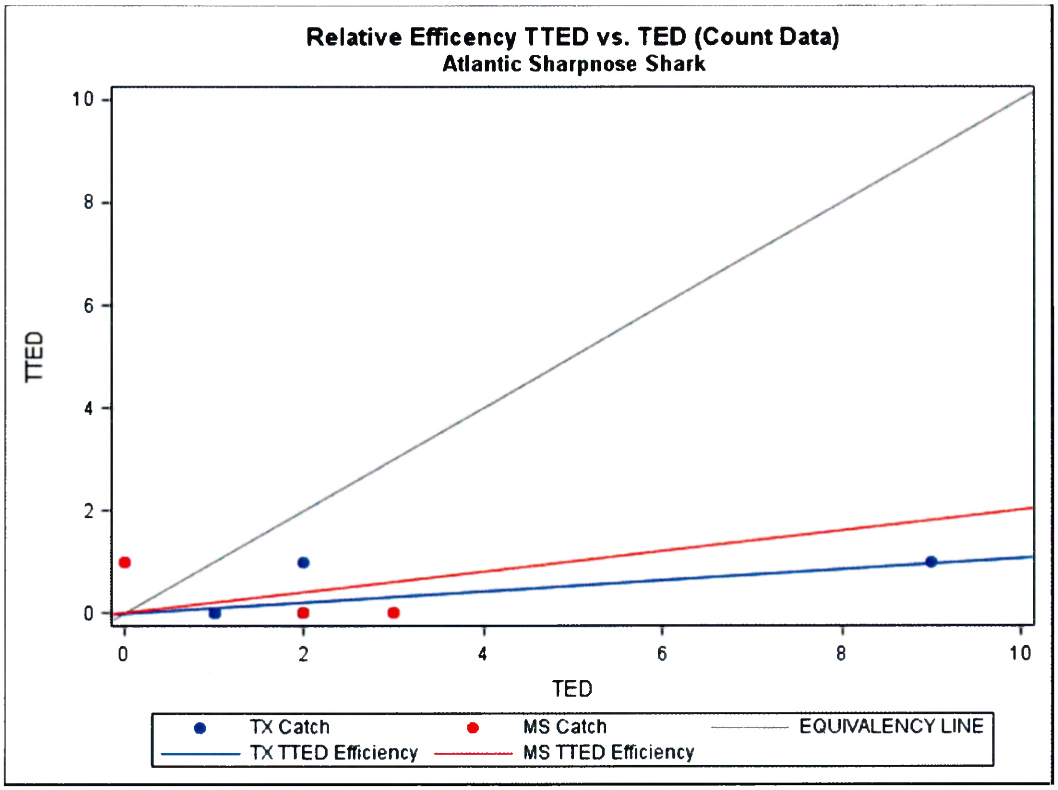


Figure 17. GA Bonnethead Shark Relative Capture Efficiency (TTED versus TED).
Results from the 2012 Georgia cruise. Analysis of the pooled data indicated that the intercept only model was the most appropriate specification. The estimated relative efficiency for Bonnethead Shark is shown as the blue line. The gray line has a slope of one to simulate equal relative efficiency of the TTED-equipped trawl relative to the TED-equipped trawl.

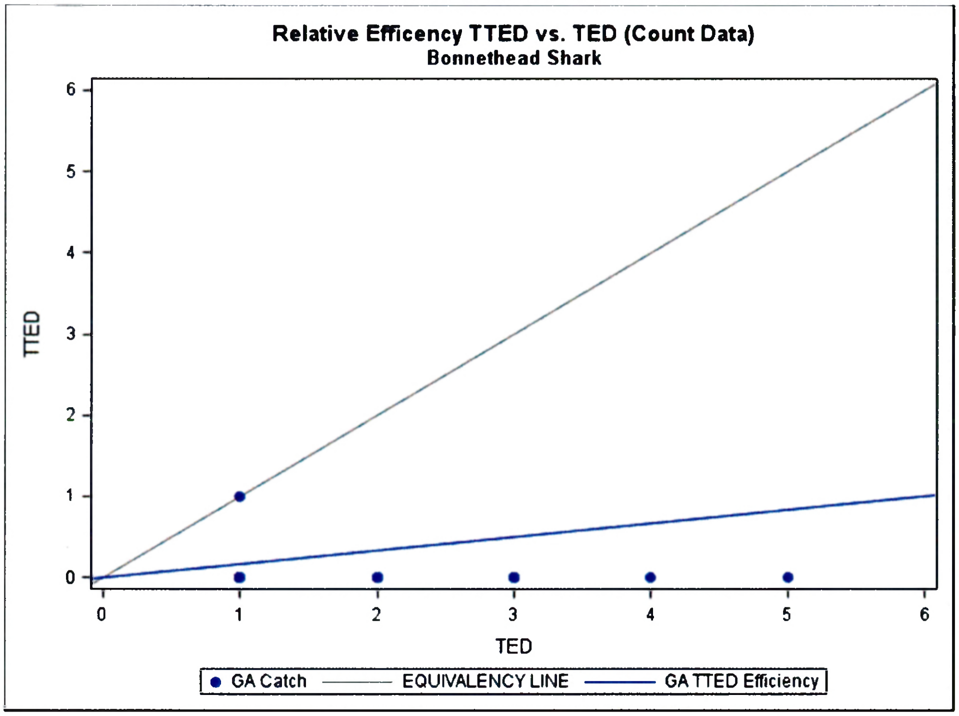


Figure 18. GA, TX, and MS Rays and Skates group Relative Capture Efficiency (TTED versus TED).

Results from the 2012 Georgia, Texas and Mississippi cruises. Analysis of the pooled data indicated that the intercept only model was the most appropriate. The estimated relative efficiency for the rays and skates group is shown as the blue line. The gray line has a slope of one to simulate equal relative efficiency of the TTED-equipped trawl relative to the TED-equipped trawl.

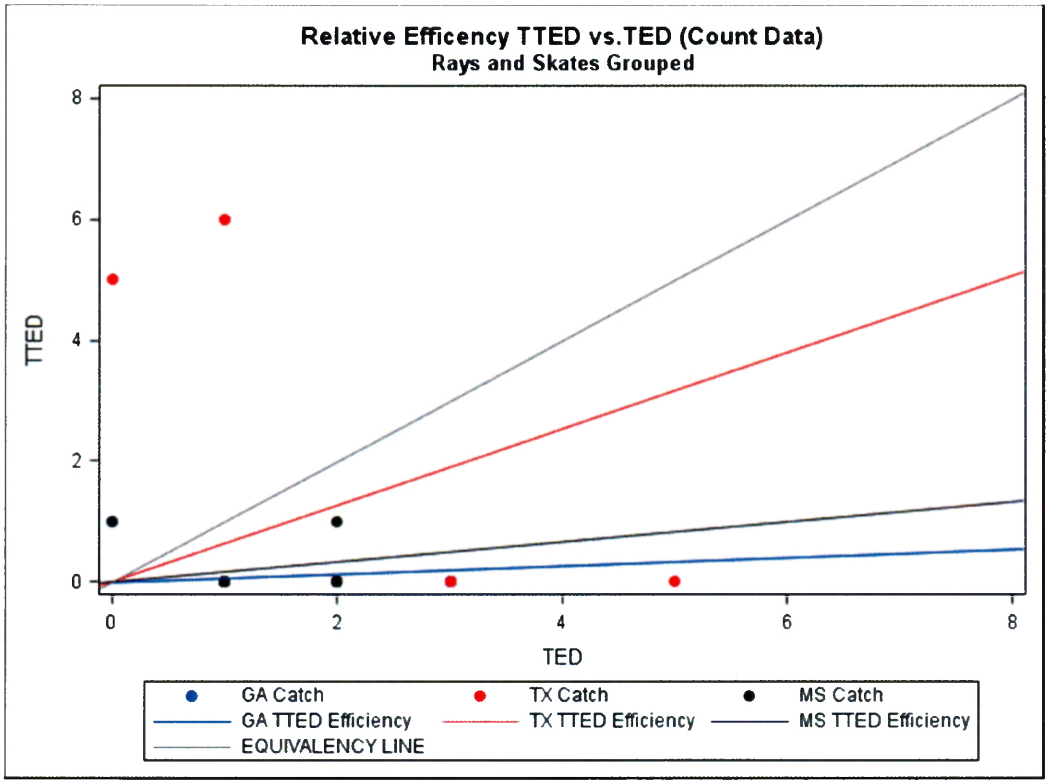


Figure 19. TX Blackear Bass Relative Capture Efficiency (TTED versus TED).
Results from the 2012 Texas cruise. Analysis of the pooled data indicated that the intercept only model was the most appropriate. The estimated relative efficiency for Blackear Bass is shown as the blue line. The gray line has a slope of one to simulate equal relative efficiency of the TTED-equipped trawl relative to the TED-equipped trawl.

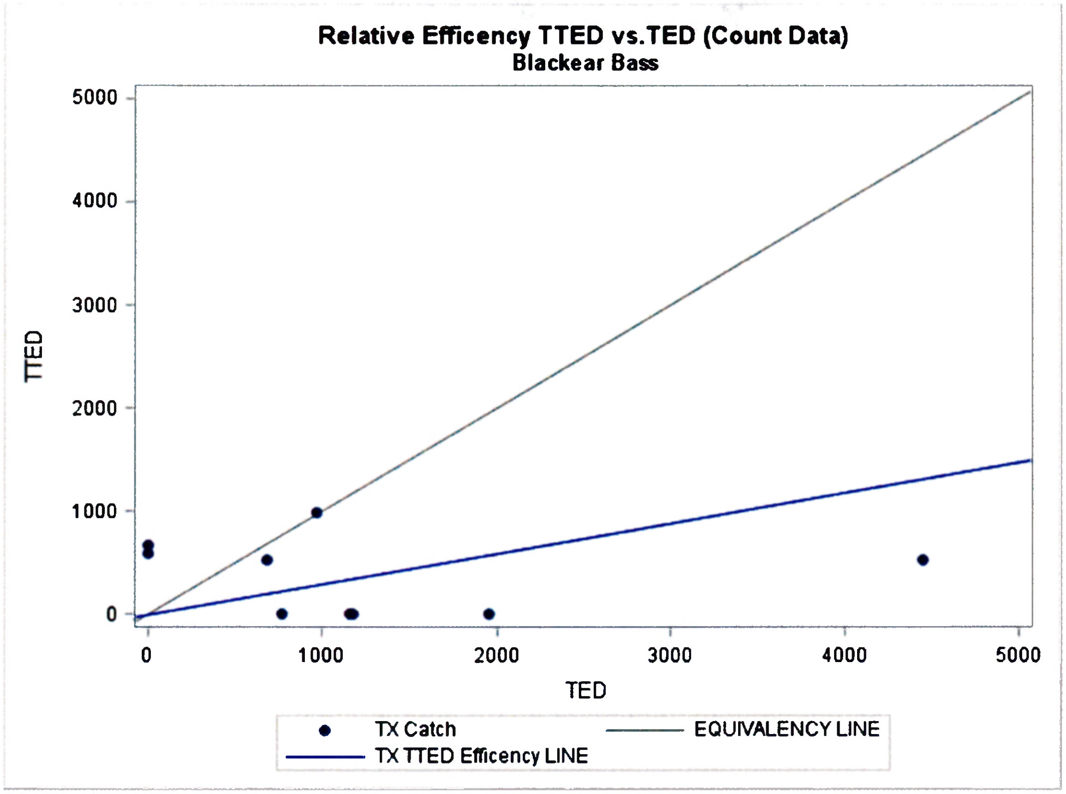


Figure 20. TX Vermillion Snapper Relative Capture Efficiency (TTED versus TED).
Results from the 2012 Texas cruise. Analysis of the pooled data indicated that the intercept only model was the most appropriate. The estimated relative efficiency for Vermillion Snapper is shown as the blue line. The gray line has a slope of one to simulate equal relative efficiency of the TTED-equipped trawl relative to the TED-equipped trawl.

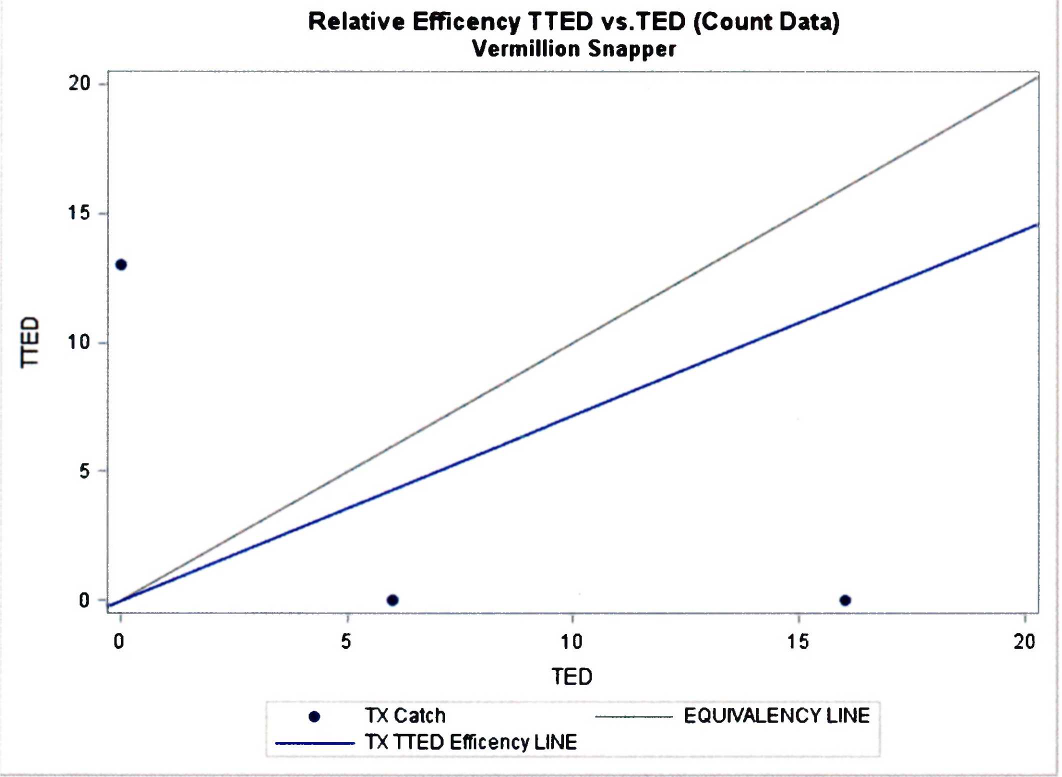


Figure 21. MS Whitings Relative Capture Efficiency (TTED versus TED).
Results from the 2012 Mississippi cruise. Analysis of the pooled data indicated that the intercept only model was the most appropriate. The estimated relative efficiency for Whitings is shown as the blue line. The gray line has a slope of one to simulate equal relative efficiency of the TTED-equipped trawl relative to the TED-equipped trawl.

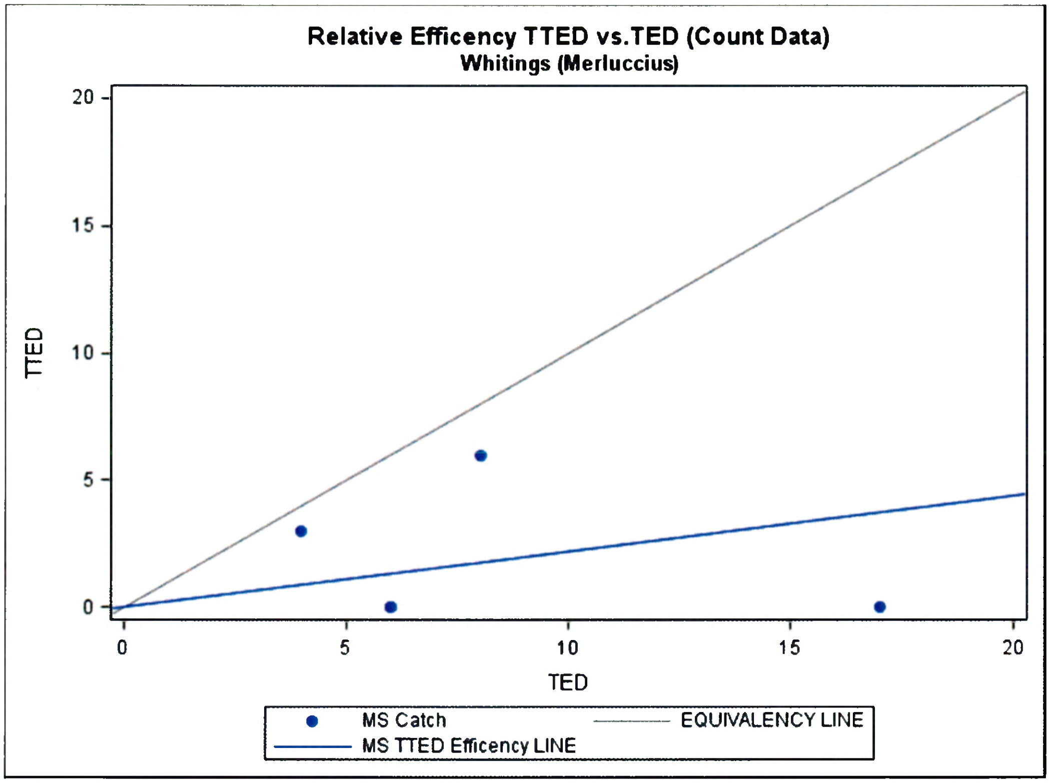


Figure 22. Plot of Grouped Small Fish Catch Weight (For All Cruises).

Plot of small fish weight from the 2012 Georgia, Texas and Mississippi cruises. The gray line has a slope of one to simulate equal small fish catch weight of the TTED-equipped trawl relative to the TED-equipped trawl. The total small fish bycatch reduction efficiency for grouped small fish is shown as the blue, red and black lines for the Georgia, Texas and Mississippi cruises, respectively.

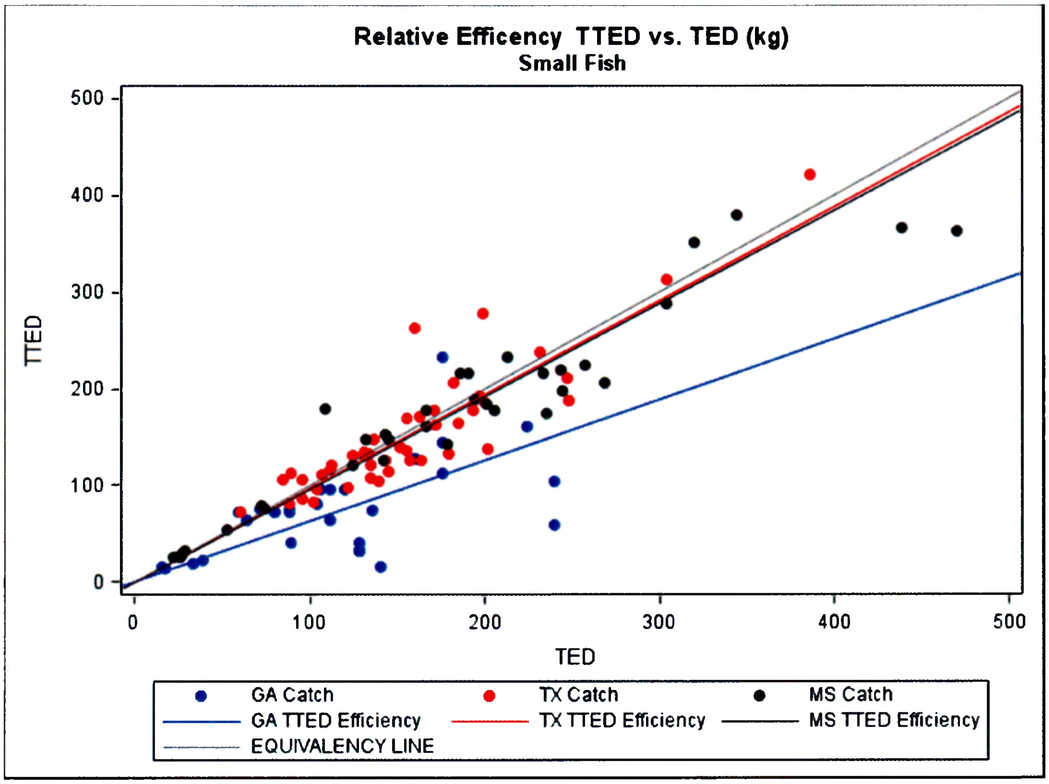


Figure 23. Shrimp Catch Weight for All Cruises Relative Capture Efficiency (TTED versus TED). The 2012 Georgia cruise analysis of the shrimp catch weight data indicated that for the intercept only model was the most appropriate. For the Texas and Mississippi cruises analysis of the shrimp catch weight data indicated that for the intercept plus the variable total bycatch reduction (kg) was the most appropriate. The shrimp catch weight capture efficiency is shown as the blue, red and black lines for the Georgia, Texas and Mississippi cruises, respectively. The gray line has a slope of one to simulate equal relative efficiency of the TTED-equipped trawl relative to the TED-equipped trawl.

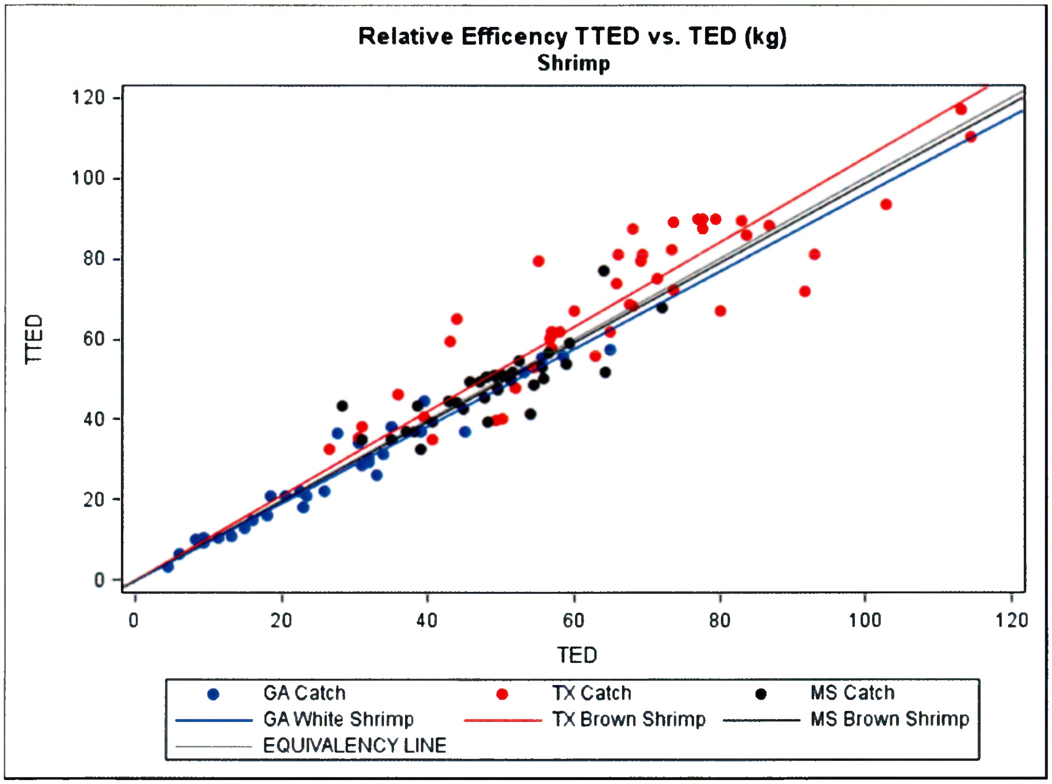
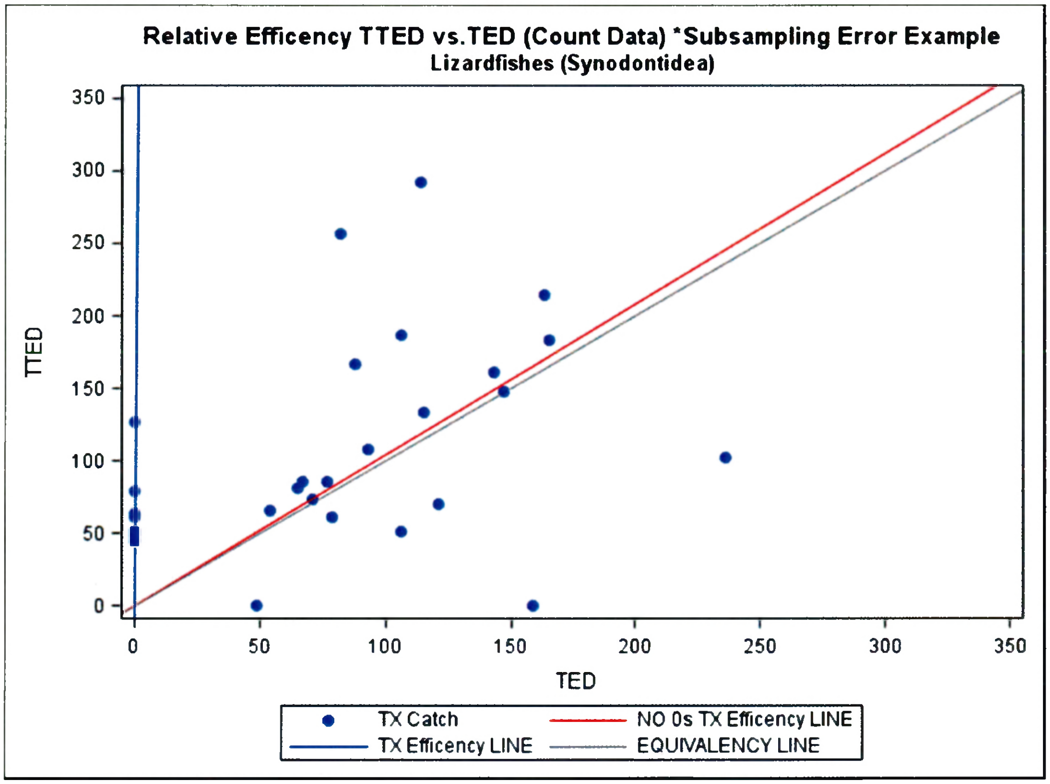


Figure 24. Simulated Lizardfishes Relative Capture Efficiency (TTED versus TED) When Tows with Zero Counts Data from the TTED or TED were removed.

Results from the 2012 TX cruise. Analysis of the pooled data indicated that the intercept plus tow depth model was the most appropriate. The estimated relative efficiency for lizardfishes is shown as the blue line. The estimated relative efficiency for lizardfish when tows with zero count data from the TTED and TED are removed is shown as the red line. The gray line has a slope of one to simulate equal relative efficiency of the TTED-equipped trawl relative to the TED-equipped trawl.



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