FINAL REPORT

Fate of Released Bycatch for the Menhaden Purse Seine Fishery Occurring off the Coast of Louisiana

LGL

Ecological Research Associates, Inc.

FINAL REPORT

Submitted to:

Steve Vanderkooy
Gulf States Marine Fisheries Commission

Prepared by:

Scott Raborn, Ph.D.
PRESIDENT-BIOSTATISTICIAN

Peter Mudrak, Ph.D.
SENIOR FISHERIES BIOLOGIST

Lewis Naisbett-Jones, Ph.D.
SENIOR FISHERIES BIOLOGIST

LGL Ecological Research Associates
4103 Texas Ave. STE 211,

Version History:

Date:	Version:
May 30, 2025	Draft, V1

www.lgl.co

MAY 2025
LGL REPORT #8

Table of Contents

Objectives

The overreaching goal of this study was to work cooperatively with the LA commercial purse seine fishery to characterize and provide scientifically robust estimates of bycatch (released and retained) across the entire 28-week purse seine season that extended from April 15th through October 31st, 2024. This goal is broken down into six project objectives (as described below).

Objectives 1 through 4 were completed in 2024 and are described in a series of progress reports submitted by LGL to GSMFC (Reports 1-7). This Report describes the methods and our findings regarding the near-term mortality study. A subsequent report detailing the results of the bycatch estimation portion of the study is to be submitted in early June 2025 to satisfy Objective 5. This report is structured so that the methods and results can be reformatted and submitted by LGL for publication in peer-reviewed journals following final revisions and acceptance of this report by GSMFC (e.g., to meet Objective 6). The six project objectives – both completed and in progress – are as follows:

1. Conduct a pilot (i.e., proof-of-concept) study during the 2023 season to refine the sampling techniques and test any necessary modifications that will ensure logistical feasibility of achieving targeted sample sizes during the 2024 season. **Deliverable**: Test every field technique to be implemented and record the workdays required for each; completion of these activities will occur by the end of October 2023. Completed.

2. Evaluate the outcomes of the pilot study, fine-tune methods to incorporate lessons learned, and conduct off-season dock-side vessel visits as necessary. **Deliverable**: A report was provided detailing our findings and recommendations for any changes to the methods proposed. Completed.

3. Carry out a full season of bycatch characterization that covers >2% of the total sets made by the fishery in LA and adjacent federal waters. **Deliverables**: (1) A report midway through the that described progress of the field study. (2) A report at the end of the field season that described the spatiotemporal sampling coverage of the fishery. Completed.

4. Conduct fate studies to estimate the near-term mortality of released bycatch. **Deliverables**: The progress reports for Objective 3 will also include assessments of this objective. Completed.

5. Clearly describe the results of the study, the methods on which they were based, and the implications of our findings. **Deliverable**: A final report will be submitted in June 2025 following analysis of the data collected during the 2024 season. In-progress.

6. Develop a manuscript or series of manuscripts that will be submitted to peer-reviewed fisheries journals. We anticipate this objective will occur simultaneously with Objective 5. **Deliverable:** The resubmission(s) to the chosen journal(s) following peer-review by their respective referees. In-progress

Survival Study

Introduction

Incidental catch, or bycatch, of non-target species in commercial fisheries is a well-recognized and long-standing issue in marine conservation and fisheries management (Harrington et al., 2005; Jennings and Kaiser, 1998). Although quantifying the harvested component of fisheries mortality can be straightforward, generating mortality estimates for released (or discarded) bycatch is far more challenging. In some commercial fisheries, a sizeable and diverse quantity of the total catch may be discarded at sea (Alverson et al., 1996; Benoît et al., 2012; Harrington et al., 2005). These discards are often driven by the lower profitability of bycatch relative to the target species (Pascoe, 1997), due to limitations to holding and processing capacities (Patrick and Benaka, 2013), and following restrictions to the amount of bycatch that can legally be harvested (O'Keefe et al., 2014). While it is assumed that some quantity of the bycatch discarded survives, post-release mortality can be substantial (Pascoe, 1997; Raby et al., 2015). A challenge for fisheries managers is that post-release mortality rates for specific fisheries are rarely known, and when studied, estimates generally cannot be applied across fisheries or species given variation in gear types, handling procedures, environmental conditions, and numerous other factors that affect species-specific mortality rates. Consequently, the uncertainty surrounding discard mortality in commercial fisheries remains a considerable barrier to effective marine resource management globally.

In recent years, our understanding of post-release mortality of bycatch has increased substantially for some commercial fisheries and bycatch species (Muir et al., 2022; Sulikowski et al., 2020; Whitney et al., 2021; Raby et al., 2015). Although at-sea studies are often costly and labor intensive, a suite of tools are potentially available to researchers for estimating released bycatch mortality. Studies utilizing tagging methods to track released fish and to estimate survival from mark-recapture analysis have been utilized in a number of fisheries (Benoît et al., 2020; Sulikowski et al., 2020). Metrics of vitality, such as Reflex Action Mortality Predictors (RAMP) have recently grown in popularity and show promise for predicting delayed mortality for a range of species (Campbell et al., 2010; Cook et al., 2018; Davis, 2007; Stoner, 2012; Raby et al., 2015). By far the most commonly applied approach throughout the bycatch literature involves holding experiments whereby released fish are temporarily housed in captivity to allow assessment of short-term mortality (Colotelo et al., 2013; Eskelund et al., 2019; Gutowsky et al., 2015; Raby et al., 2015). While each method has its limitations (reviewed by Neilson et al., 2012), these approaches to estimating survival represent a significant advance from otherwise unquantified discard mortality rates. Moreover, when methods are deployed in concert they can result in robust estimates of post-release mortality (O'Keefe et al., 2014; Raby et al., 2015).

The Gulf menhaden (*Brevoortia patronus*) reduction fishery is the largest commercial fishery in the Gulf of Mexico (GoM) and the second largest fishery in the contiguous U.S. in terms of total landings (Vaughan et al., 2007). Menhaden are sought after due to their high oil content and their protein used to produce a variety of commercial products (Guillory and Hutton, 1982). Landings peaked around 1,000,000 metric tons in the 1980's and have averaged ~400,000 metric tons over the last decade (2014-2024). The fishery employs purse-seines to capture schools of menhaden during the commercial fishing season (April to October) and primarily operates along the coasts of Louisiana and Mississippi (GSMFC, 2015). In 2024, 27 fishing vessels were in operation, each carrying two purse seine boats that deploy half of the purse net, and 5 run boats which lack purse seine boats. The near-surface schools of menhaden are relatively easy to target, and fishing vessel captains are aided by a fleet of spotter planes that direct them towards the catch.

As with almost all fisheries worldwide, in addition to target species, Gulf menhaden purse boats can encounter unwanted bycatch (Condry, 1994; De silva, 1998; Sagarese et al., 2016). Although previous menhaden bycatch studies are sparse and often with substantial limitations (Reviewed by Sagarese et al., 2016), past estimates of incidental catch approached ~36,000 sharks and ~28,000 red drum during the 7-month commercial fishing season (De Silva et al., 2001). The gulf menhaden industry began efforts to reduce bycatch starting in the 1950s, and continues to support measures to reduce unwanted incidental catch (NOAA, 2024; Rester and Condrey, 1999). Industry designed and currently deploys two bycatch excluder devices to reduce the take of large bycatch species by instead releasing them at sea. Previous studies, however, have raised concerns over the potential for unaccounted mortalities in the released bycatch component (De Silva et al., 2001), with recent concerns centering around the negative impacts on economically important teleost's such a red drum and spotted seatrout (LDWF, 2024a; Sagarese et al., 2016). Despite the potential for released bycatch mortality, no studies have experimentally investigated the post-release survival of bycatch in the Gulf menhaden reduction fishery. Unlike other commercial fisheries where condition scores are paired with tagging or holding studies to estimate post-release survival (Kaimmer and Trumble, 1998), no such comparison has been made in the Gulf menhaden fishery. Even the most basic data useful for inferring post-release survival rates for most species are lacking.

To better understand the magnitude of incidental fishing mortality for discarded species in the Gulf menhaden reduction fishery, we investigated post-release mortality of released bycatch alongside an at-sea observer program conducted during the 2024 fishing season. Specifically, we conducted a ~24-h holding study to evaluate mortality rates of red drum (*Sciaenops ocellatus*), black drum (*Pogonias cromis*), and gafftopsail catfish (*Bagre marinus*) discarded via industry bycatch excluder devices. For fish tested in the ~24-h holding study, we further assessed reflex responses as predictors of mortality using the RAMP approach recently utilized in other commercial purse seine fisheries (Raby et al., 2015). Lastly, to assess viability of all bycatch species released at sea, including rarer bycatch or species not-suitable for on-board holding studies, we assigned condition scores for all released bycatch species encountered during the 2024 at-sea observer program. As a result, this study provides a long-awaited estimate of post-release mortality for key discard species in the Gulf menhaden fishery and represents the most complete and comprehensive assessment of released bycatch condition conducted in the fishery to date.

Materials & Methods

Study Area & Conditions

This study was conducted during the 2024 Gulf menhaden (*Brevoortia spp*.) commercial purse seine fishing season (April 15th to October 31st, 2024). During the season, a total of 13,144 sets were fished in Louisiana state waters or adjacent federal waters. This survival study was conducted alongside a bycatch characterization study utilizing at-sea observers to characterize bycatch within the fishery. All fish used for the survival study were collected by at-sea observers from commercial purse seine nets fished in Louisiana state waters or adjacent federal waters (Figure 1). In total, 311 fish were collected from 90 sets between April 15th to October 15th, 2024 and used in an on-board holding study to estimate survival of the released bycatch component of the fishery. Sets ranged in size from 5,000 to 450,000 estimated standard menhaden and covered depths ranging from 10-48 ft. Sea-surface conditions measured at each set location varied by month and location, with temperatures ranging from 23.3 °C to 33.9 °C, and salinities from 3 ppt to 32 ppt across the study period.

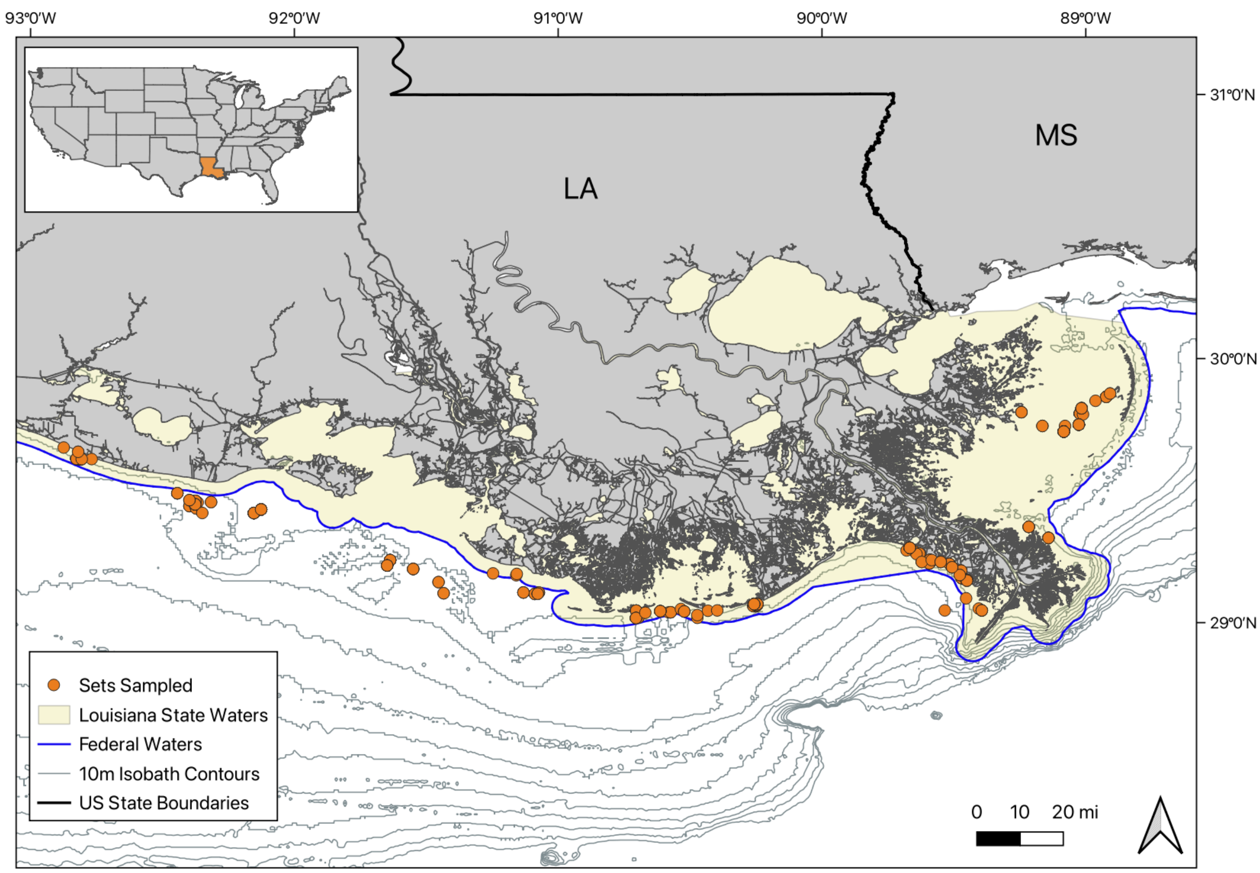


Figure 1. Study area in coastal Louisiana, United States. Shown are the locations of the 90 net sets (orange circles) from which fish were sampled and used in the holding study.

Fishing Gear & Methods

The Gulf menhaden purse seine fishery operates via multiple vessels. Fishing vessels (up to ~195 ft in length) are equipped with a large, refrigerated hold for transporting catch, and twin stern ramps that are used to deploy two, much smaller purse boats (~39 ft in length). A second set of vessels operate as “run boats” that pump catch directly from the nets (or holds) of fishing vessels into their own holds. Run boats reduce the catch burden on fishing vessels by allowing them to remain at sea for longer periods before transporting their catch back to shore. This study was conducted from run boats, which are absent of purse boats and thus provided ample crew space for at-sea observers and deck space for the two, large holding tanks used in the ~24 hr holding study. Importantly, run boats process catch using the same procedures as fishing vessels in the fleet, thus all released bycatch sampled from nets pumped by run boats experienced replicate conditions to bycatch that is processed by fishing vessels within the same fleet. Samples were only collected from net sets pumped directly by the run boat, and retained catch pumped from the holds of fishing vessels was not sampled.

Commercial purse seine gear utilized by the industry varies by fishing vessel but generally consists of a 1,000-1,400 ft long and 65-90 ft deep purse seine with 1 ¾ inch mesh size. Net materials also differ between fishing vessels, consisting of nylon fiber or high-strength polyethylene fiber (e.g., Dyneema®), or a combination of both, with higher-strength materials typically being used in the net bunts. During fishing operations, nets are deployed by the two purse boats, each one carrying and releasing half of the purse net. Purse boats are directed to the school of menhaden by fish-spotting aircraft overhead, or by spotters in the wheelhouse of the fishing vessel. Upon encircling the target school of fish, along with any incidental catch, the purse crew drop a 600 lb ‘tom’ weight to close the net opening. The net leadline has a series of rings threaded with a purse line that is used to bring the net wings towards the tom weight. The crew operates a winch coupled to the main engine to pull the lines towards the purse boats, bringing the catch into a more compact school. The time required to set and retrieve purse nets varies depending on the size of the catch and the experience of the crew and can range from ~30 minutes to multiple hours for particularly large sets (e.g., over 500,000 fish).f

Once the net is tight with fish, the fishing vessel (or a run boat) pulls alongside to secure the net and to retrieve the catch (Figure 2a). A large 25-cm diameter flexible suction hose, primed with saltwater, is lowered into the tightly packed net. The flexible hose is equipped with a hose cage, utilized by industry as a bycatch excluder device to prevent large fish from being drawn into the pump system, and to prevent the purse net from being ensnared in the pump (Figure 2b) (Rester and Condrey, 1999). Once the hose cage is submerged, a centrifugal pump is engaged to draw the fish through the hose to the top of the pump house. Here, the catch passes across a fish excluder grate that acts as a secondary bycatch sorting mechanism (Figure 2c). Menhaden and smaller bycatch constituents pass through the fish excluder grate and are dispersed across the vessel’s hold via a series of bow and stern loading chutes and deflectors controlled by the crew (Figure 2c). Water drawn in by the centrifugal pump is eliminated from the pumping operation via a dewatering screen and is directed overboard via a discharge chute. Bycatch specimens too large to fit through the fish excluder grate are shunned down a separate release chute and released overboard. At the end of the pumping operation (e.g., when few menhaden remain in the purse net), large bycatch excluded from the pump via the hose cage is then released directly from the purse net by the purse crew by rolling bycatch over the float line. As a result, there are two distinct ways in which bycatch is released during a set: (1) fish excluded by the hose cage that are released from the net by the crew (hereafter referred to as “rollover bycatch"), and: (2) fish that travel through the pump, are excluded by the fish excluder grate, and are released via the release chute (hereafter referred to as "chute bycatch"). To produce survival estimates for both aspects of the released bycatch, at-sea observers collected fish from both the rollover and chute bycatch for the holding study.

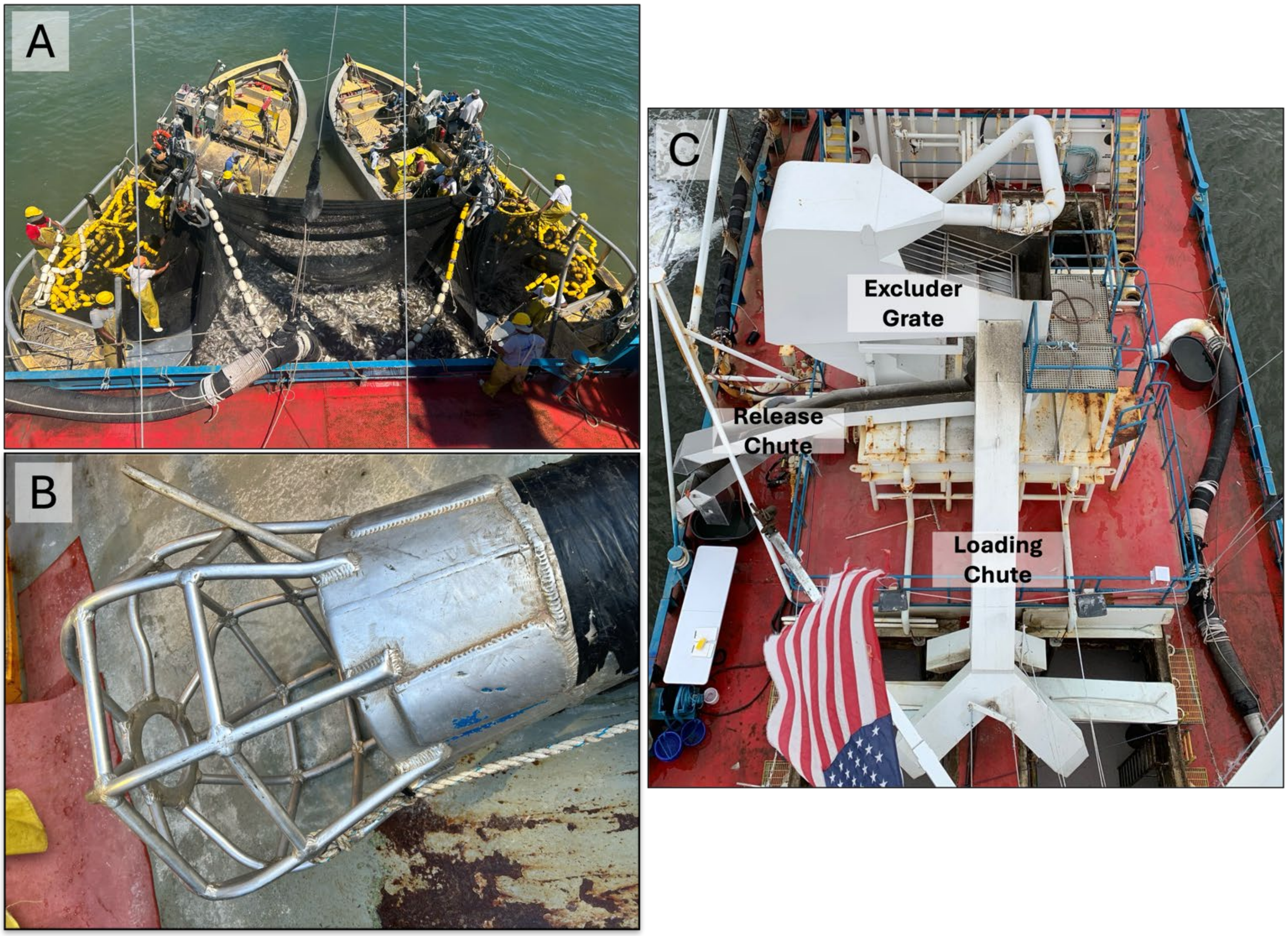


Figure 2. (A) Purse boats alongside the sampling vessel with catch being pumped from the net via the large suction hose. (B) The hose cage used as a bycatch reduction device to prevent large bycatch from being entrained within the hose and pump. (C) Standard vessel layout showing the loading and release chutes and the fish exclude grate used as a secondary bycatch excluder device.

Fish Collection & Handling

Three species were selected for the ~24-h holding study based on their commercial and recreational interest, suitability for confinement experiments, and their frequency of occurrence in the released bycatch (e.g., to allow for sufficient sample sizes). Select species were red drum, black drum, and gafftopsail catfish. When available, red drum were preferentially selected for inclusion in the survival study given that they are of particularly high recreational and economical value within the study location, and across much of the southeastern US and Gulf of Mexico Coasts. Total sample sizes of 157 red drum, 88 black drum, and 66 gafftopsail catfish were tested in the holding study during the fishing season. Although cownose rays (*Rhinoptera bonasus*), sharks (*Carcharhinus sp.*), and crevalle jack (*Caranx hippos*) were also observed in large enough quantities within the released bycatch component, these species were not included in the holding study due to their poor suitability for confinement experiments (e.g., ram ventilators or active pelagic swimmers), or given safety concerns relating to handling by at-seas observers (e.g., the barbs of cownose rays). These species, along with all released bycatch species encountered by the on-board observers, were assigned condition scores to infer fates as described below.

The chute bycatch was sampled by diverting the release chute, which normally shunts fish overboard, back on board the vessel and into a water-filled 100-gallon tank (Figure 3c). During sets when at-sea observers were not sampling, the entrance to the diversion chute was closed and fish were released overboard in the normal fashion. So as not to alter fish survival, the diversion chute and 100-gallon recovery tote were designed to replicate, as best as possible, the typical conditions fish travelling down the release chute would experience (e.g., landing in seawater after travelling down the chute). An onboard saltwater hose was used to flush the 100-gallon recovery tote between sets. This was sufficient for maintaining suitable oxygen levels and water temperatures (e.g., equivalent to local sea surface conditions). During the pumping operation, an at-sea observer monitored the chute for released bycatch. All non-candidate species that entered the recovery tote were removed by observers to avoid temporary overcrowding, and to minimize interactions between sharks and rays and the species to be used in the holding study. All candidate species for the holding study that entered the recovery tote were inspected, and if not already deemed a mortality, were promptly tagged and transferred into the larger holding tanks at the stern of the vessel using non-abrasive, silicone coated dip nets. Transfer of fish between the recovery totes and the holding tanks at the stern of the vessel resulted in ~30 seconds of air exposure.

The rollover bycatch was sampled by at-sea observers using long-handle landing nets to sample bycatch directly out of the purse net as they were rolled out by the crew (Figure 4). Rollover bycatch candidate species collected in the landing nets were hoisted vertically over the port railing and placed in a second, identical 100-gallon recovery tote located at the stern of the vessel. Transfer of fish from the purse net to the rollover recovery tote via the landing nets resulted in ~30 seconds of air exposure. Beginning in September, at-sea observers utilized a large brailer net (56 x 56") and winch to transfer bycatch individuals onboard (Figure 4) to collect a higher percentage of the rollover bycatch from high bycatch sets (>30 individuals). Utilization of the brailer could result in longer air exposure times ~60 seconds, and the potential for physical trauma from crushing. Therefore, if the brailer was used, only a small number of individuals from the top layer of the net were used in the survival study to minimize any effects of trauma on fish survival. Regardless of collection method, any fish that could not be immediately transferred to the holding tank was not used in the survival study, and any individual deemed to be a mortality by the at-sea observer was not included in the holding study.

All fish used in the 24-h holding study were double tagged with two conventional dart tags (Floy Tag and Manufacturing, Seattle, Washington, USA; FT1 Dart Tags, 12 cm long) immediately prior to being transferred into the holding tanks. Each dart tag was inserted into the dorsal musculature using a stainless steel tag applicator. Tag numbers were used to identify individual fish, and linked fish to their set of origin as well as denoted whether fish originated from the chute or rollover bycatch components. Conventional tagging was conducted efficiently and quickly (<60 seconds), with fish temporarily placed on a tagging table for the procedure. All fish were weighed and measured at the conclusion of the ~24-h holding experiment to minimize handling stress prior to determining fate and assessing reflex impairment.

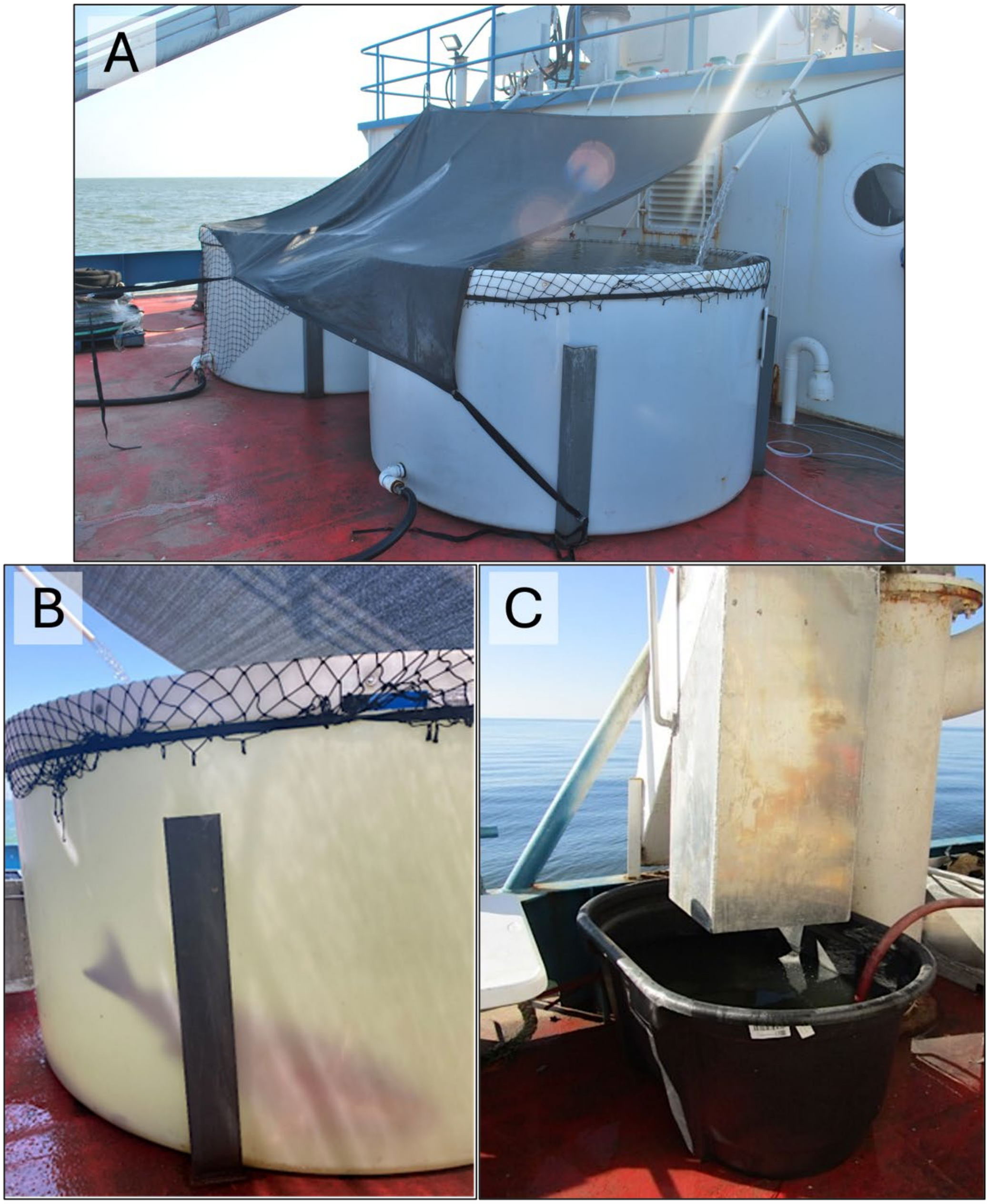


Figure 3. (A) Photo showing the two large (~1250 US Gallon) circular holding tanks positioned at the stern of the F/V Vermilion. (B) Photo of a red drum that was housed in a tank during the ~24-h holding period to estimate short-term survival. (C) Release tote within which chute bycatch were temporarily housed prior to transfer to the larger holding tanks.

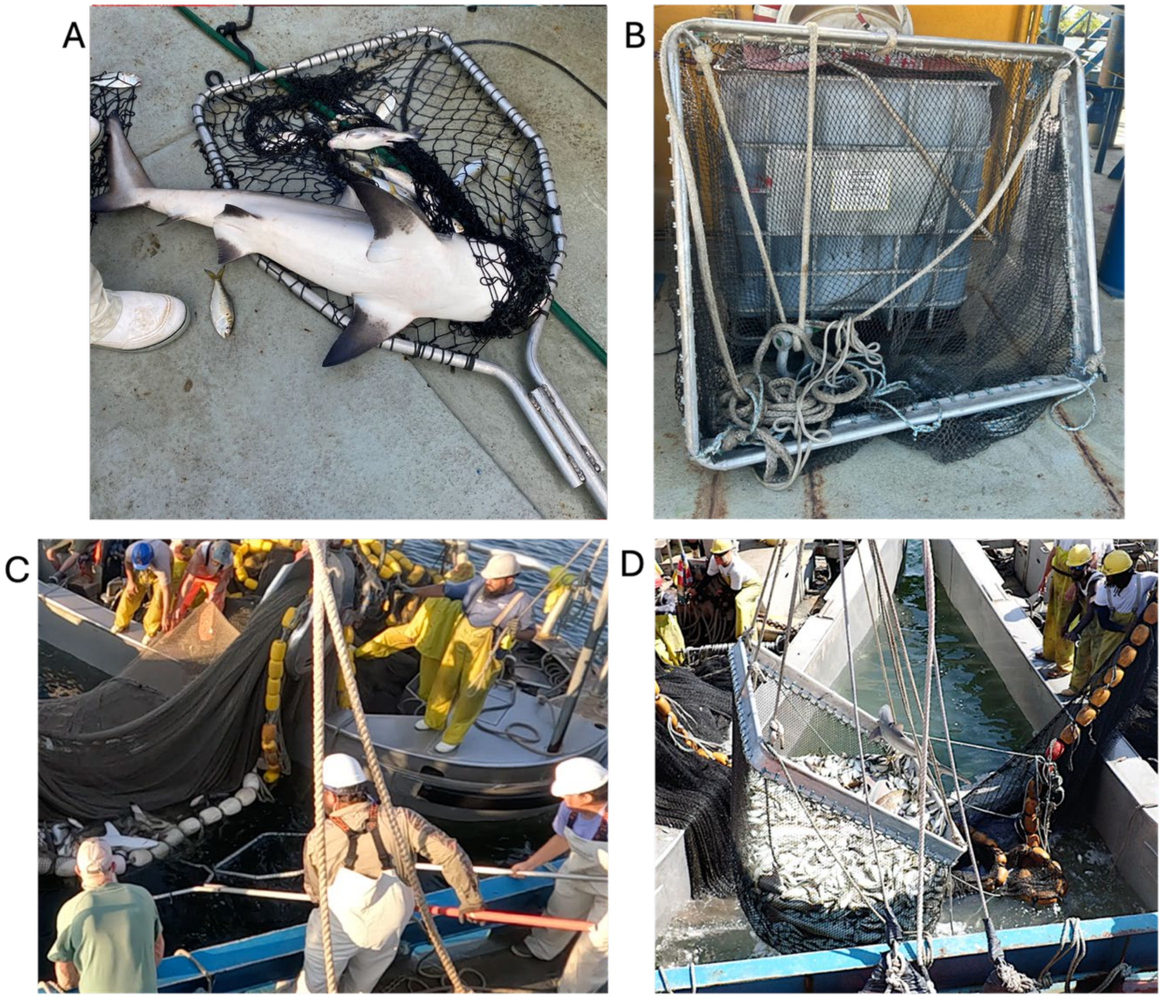


Figure 4. (A) Long-handled landing nets used to subsample the rollover bycatch (frame dimensions 29” w x 40” l; handle: 100”); (B) A brailer net (60” deep) and frame (56 x 56”) used for sampling sets with higher bycatch numbers; (C) Large sharks and rays, as well as a small quantity of leftover menhaden, being rolled over the float line and into the observer’s nets after menhaden have been pumped out of the purse net; (D) For selected high bycatch sets, bycatch and leftover menhaden were rolled into the brailer net and winched onboard the run boat.

Reflex Impairment

Reflex impairment for all fish utilized in the holding study was assessed via a series of simple reflex responses that have been previously validated as predictors of mortality in marine fishes (Davis, 2010; Raby et al., 2015). Specifically, we used Reflex Action Mortality Predictors (or RAMP scores) to objectively check for the presence or absence of simple reflex responses used to produce a reflex score. This approach has been widely used to assess the fate of incidental catch, including previous studies assessing bycatch from purse seine fisheries (Raby et al., 2015). In brief, this involved checking for the presence or absence of five key reflexes (tail grab, body flex, head complex, orientation, and vestibular-ocular response), each assessed as described in (Davis, 2010). For each fish, all five reflex responses were assigned a score of 0-1, with a score of 1 indicating a reflex action that was impaired. Thus, higher cumulative RAMP scores correspond to fish that exhibited a higher degree of reflex impairment. RAMP score assessments required <15 seconds to complete and were conducted at two timepoints during the study: (1) as fish were released into the holding tanks for the first time, and (2) immediately after fish were removed from the tanks at the end of the ~24-hr holding period.

24-h Holding Study

The holding study was conducted on board the F/V Vermilion of Ocean Harvesters and the F/V Kittiwake of Westbank Fishing, representing the two fishing companies engaged in the gulf menhaden commercial reduction fishery. Each vessel housed two large (~1250 US Gallons), circular holding tanks (90" diameter x 48" height) (Figure 3). The holding tanks were positioned on the deck near the stern of each vessel, with one tank located at each of the port and starboard sides of the engine room. Tanks were covered with netting to prevent fish from escaping the tank and covered with a 90% shade cloth to minimize exposure to direct sunlight (Figure 3). Tanks received a constant flow of fresh sea water extracted via the vessel's on-board saltwater pump. Flow rates varied slightly by tank and by vessel (range: 28 to 36 gallons per minute), but were sufficient for maintaining temperature, salinity and oxygen conditions similar to ambient recordings.

The tanks were used to hold bycatch for a target duration of 24-hrs after capture to monitor short-term survival. This 24-hr period was chosen because longer periods of confinement would restrict the number of replicates that could be completed during the 5-day commercial fishing week, and because this duration was consistent with that used in past studies of released catch mortality in salmon purse seine fisheries (Raby et al., 2015). Bycatch species of interest for the holding study were not present in every net sampled by observers. In order to meet sample size goals, fish were therefore collected from up to 7 different net sets to fill a single holding tank, with some bycatch being added to the tanks up to ~8 hours after the first individuals. Introduction of new bycatch to each holding tank was ceased when a predetermined stocking density threshold, equating to ~1 lb of fish per 10 gallons was neared (mean stocking density = 1.06 lb per 10 gallon; Stdev = 0.54).

Fishing operations continued throughout the period that fish were held in the tanks. Weather conditions were generally calm, with winds rarely surpassing 15 knots and waves generally less than 3 ft, conditions needed for industry to successfully spot menhaden and to safely deploy purse boats. On occasion, the fishing vessels anchored in or traveled through shallow nearshore areas that could cause sediment to be pumped through the flow-through system, or travelled to the dock to unload catch through waterways with salinity or dissolved oxygen levels below those experience by fish in the menhaden fishing grounds. To avoid exposing fish in the holding tanks to high sediment loads, freshwater, or hypoxic conditions as the vessel transited through these areas, the flow-through systems were temporarily shut off and tank oxygen levels were maintained via a series of aerators and sump pumps to increase flow. Holding tank conditions were monitored constantly during the entire holding period so that tank water conditions could be assessed *post hoc*. A dissolved oxygen logger and a conductivity logger reporting temperature and salinity were set to measure water parameters at 1-minute intervals (HOBO Loggers: U26-0001 & U24-002-C, Onset Computer Corp., Bourne, Massachusetts, USA). Loggers were calibrated regularly, housed in protective PVC cases, and positioned in the middle part of the water column, above tank sediment deposits. Water parameters recorded by loggers were further calibrated by means of independent measurement taken by a Yellow Springs Instrument (YSI) multiparameter probe daily for each holding tank.

The onboard tanks were monitored by at-sea observers during the confinement period and dead fish were removed from the tank as they were discovered. Live fish within the holding tanks were easily able to evade capture at the end of their holding period. Therefore, to retrieve the surviving fish without causing excessive stress to the fish remaining within the tank, after the last fish added to the tank had been confined for 24 hours, the tanks were drained, and all fish were removed via dipnets. This approach resulted in differences in the duration of confinement between individuals, with the individuals added to the tanks first experiencing longer holding times. This outcome is not uncommon given the practical constraints of confinement studies within active commercial fisheries, and similar differences in holding times have been reported in other survival studies within commercial purse seine fisheries (Raby et al., 2015). Additionally, the ceasing of fishing operations occasionally required the at sea observers to release fish in the holding tanks prior to the full ~24-h holding period.

For each individual removed from the tanks at the end of the holding period, RAMP scores were reassessed (if alive), weights and lengths recorded, and their fate determined. For live fish, weights were recorded by placing each fish in a non-abrasive bag hoisted up via a mechanical scale (Pesola Macro Line, 50 kg spring scale). Instances where tags had shed during the holding study were recorded, so that tag shedding rates could be calculated. All live individuals that survived the holding study were released with their conventional tags and printed contact information to assist with the reporting of recaptured fish by anglers. This component of the study was not designed to produce robust, long-term survival estimates. While recapturing a tagged individual does confirm its survival, the absence of a recapture could constitute any number of reasons, including mortalities, fish avoiding recapture, or the failure of a fisher to report the catch (Neilson et al., 2012). Additionally, fish released at the end of their 24-hour confinement were sometimes displaced many miles from the location of capture, including locations that may have been poorly suited for survival (e.g., within the Mississippi River, or at the dock of the menhaden processing plants).

CONDITION SCORES

Released bycatch sampled by observers far surpassed the available space in the holding tanks for testing short-term survival for all bycatch encountered. Therefore, all fish sampled from the rollover and chute bycatch, regardless of if they were used in the holding study or not, were assigned a condition score. In doing this, we were able to relate pre-release condition scores to the short-term mortality estimates produced by the holding study. Further, these condition scores were used to infer survival of encountered bycatch species that were not suitable for the holding study (e.g. cownose rays, sharks, and jack crevalle). Condition scores were assessed using the scoring criteria outlined by Benoît et al. (2010). In brief, condition was scored based on a rapid (10 s) evaluation of each bycatch specimen as they were intercepted by observers. Bycatch were assigned one of four scores according to the criteria outlined in Table 1.

Table 1. The condition scoring criteria used by at-sea observers to assess released bycatch in the menhaden purse seine fishery (Benoît et al., 2012, 2010).

Condition	Code	Description
Excellent	1	Vigorous body movement. No minor[a] external injuries.
Good/fair	2	Weak body movement. Minor[a] external injuries.
Poor	3	No body movement, but opercular movement. Minor[a] or major[b] external injuries.
Mortality	4	No body or opercular movements. Major[b] external injuries or disfigured/decapitated specimen. Dead or moribund.

[a]Minor injuries were defined as minor bleeding or tears, moderate scale loss, or moderate fin damage.
[b]Major injuries were defined as major bleeding, major tearing of body parts, damaged operculum, bloated swim bladder, or extensive scale loss (>50% coverage).

Data and Analysis

A total of 311 fish were tested in the confinement study during the 2024 fishing season with individuals tested being representative of released bycatch in the fishery in terms of condition scores (Appendix 3). A small number of individuals were excluded from our final analyses that were either housed in the tanks for too short a period to accurately assess survival (e.g., <12 hrs), or housed in tanks for too long (>36 hrs) so that the increased confinement stress risked confounding survival estimates. This approach resulted in the exclusion of three red drum from the rollover and one gafftopsail catfish from the chute that were confined for less than 12 hours. Four additional fish, including three black drum and one red drum collected from the rollover were excluded based on confinement times greater than 36 hrs in duration. This left a possible 303 fish for analysis.

Evaluation of the data logger data revealed that, on occasion, hypoxic conditions (e.g., DO <2.0 MgL^{-1}) occurred within the holding tanks. Generally hypoxic conditions occurred when the flow-through systems were shut off as vessels transited through areas of shallow or low salinity water. Although additional aeration and circulation was added to the tanks to compensate for reduced flow during these scenarios, these measures were not always sufficient for maintaining oxygen levels >2.0 MgL^{-1}. As a result, a total of 4 out of 40 replicate experiments experienced hypoxic conditions lasting longer than 1-h. We observed no discernable pattern whereby fish in hypoxic experiments expressed higher mortality rates, an observation consistent with the high hypoxia tolerance reported for some of the species we evaluated (e.g., red drum) (Ackerly et al., 2023; Ackerly and Esbaugh, 2020; Baker et al., 2023). Regardless, we employ a comprehensive approach to the analysis whereby we present the data in two ways. First, we estimate survival for all 303 fish tested in the ~24-h holding experiments that met the criteria described above, including all individuals in our analysis that were exposed to hypoxic conditions. Second, to account for the potential confounding effect of the hypoxic conditions on survival, we present survival estimates where the four experiments that experienced hypoxia >1-h in duration were removed from our analysis. To avoid biasing survival estimates, all individuals from these 4 batches were excluded regardless of fate or the duration an individual fish experienced hypoxia. These analyses are presented in tandem to allow for comparison of survival estimates produced under each criterion.

To investigate the relative importance and explanatory power of environmental predictors on survival probability, we employed Generalized Linear Models (GLMs). Such logistic regression approaches have been widely used to evaluate bycatch numbers, condition, and post-release mortality in commercial fisheries contexts worldwide (Ng et al., 2015; Smith and Scharf, 2011; Yan et al., 2022). To explore factors influencing survival, we employed an information-theoretic model selection framework (Burnham and Anderson, 2002). Rather than relying on stepwise procedures or null hypothesis testing, this approach compares a suite of a priori candidate models, each representing a biologically plausible combination of predictor variables. A comprehensive model selection framework was constructed by generating and fitting all possible combinations of five relevant predictors:

(1) Fish total length (TL),
(2) Sea surface temperature (°C)
(3) Pump time in total seconds (as a proxy for the amount time rollover fish spent in the net)
(4) Depth (ft), and
(5) Dissolved oxygen (MgL^{-1}).

Additional explanatory variables such as salinity, fish weight (kg) and set size in terms of the estimated number of standard menhaden were excluded from the models due to high degrees of correlation with existing predictors (Pearson's > 0.7). Correlation among covariates was assessed as per Dormann et. al. (2013), who found that avoiding the simple threshold of Pearson's $|r| > 0.7$ between two variables, and the use of ecological understanding to determine which variables to exclude when this threshold was reached was enough to thwart problems of collinearity.

All 2^k-1 (where k=5) unique combinations of the predictors were generated, resulting in 31 distinct candidate models. For each combination, a GLM was specified with a binomial distribution and logit link function, using maximum likelihood (ML) estimation to ensure valid comparisons across models with differing fixed effect structures (Wood 2022). Akaike information criterion (AIC) corrected for small sample sizes (AICc), was used to evaluate candidate models (Burnham and Anderson, 2002). For each model, we recorded the log-likelihood, AICc, and the number of parameters (k). Models were ranked by ΔAICc (the difference from the AICc for the top-ranked model), which were converted to Akaike weights. Akaike weights (W_i) represent the relative likelihood of each model, among all models considered, and were used to assess the relative plausibility of each candidate model. Of the suite of models investigated, Akaike weights sum to 1 and indicate how probable one model is compared with all others considered. Likelihood values and Akaike metrics for the top 10 logistic regression models that accounted for 99% of the weight (out of the 31 models) are presented.

Model diagnostics were conducted to evaluate the adequacy and assumptions of the top-ranked GLM. Likelihood ratio tests (LRT), comparing the full model to an intercept-only model were conducted to determine overall significance of the top-ranked model. To interpret the direction and strength of individual predictors for the top-ranked model, we further examined parameter estimates and significance values. Diagnostic procedures focused on residual patterns, distributional assumptions, and predictive performance. To evaluate residual behavior and model assumptions, we used standardized simulation-based residual diagnostics for GLMs. Simulated residuals were generated from the fitted model using posterior predictive simulations under the binomial error structure. Diagnostic plots and statistical tests were used to assess residual uniformity (Kolmogorov–Smirnov), overdispersion, and zero-inflation, which is particularly relevant for binary outcomes to detect excess zeros not captured by the model. To assess predictive performance, we computed the Area Under the Receiver Operating Characteristic Curve (AUC). Predicted probabilities from the GLM were compared to observed binary outcomes to generate the ROC curve. The AUC was calculated to quantify model discrimination, with values closer to 1 indicating better predictive performance. These diagnostic procedures indicated that the selected GLM was appropriately specified, with no evidence of major violations of model assumptions, overdispersion, or poor fit.

Due to sample size constraints, red drum were the only species modelled from the rollover bycatch (n=133). All analyses were conducted using R (R Development Core Team, 2014) statistical software (Version 4.3.2). Survival rates and 95% confidence intervals (CI) were calculated using the binomial Clopper-Pearson (exact) method (Clopper and Pearson, 1934). Significance was evaluated at a 5% alpha level.

Results

Capture Characteristics

A total of 153 red drum, 65 gafftopsail catfish and 85 black drum were tested in the ~24-h holding study and used in the analysis. Total lengths of red drum in the rollover bycatch ranged from 774 to 1,062 mm and for the chute bycatch 822 to 946 mm. Total lengths of black drum in the rollover bycatch ranged from 704 to 936 mm and for the chute bycatch 703 to 931 mm. Total lengths of gafftopsail catfish in the rollover bycatch ranged from 405 to 625 mm and for the chute bycatch 393 to 629 mm.

Condition Scores

The condition of fish as visually assessed by the at-sea observers for species used in the holding study are shown in Table 2. In the rollover, most individuals were assessed as being in excellent or good condition, with relatively low percentages of individuals being assessed as immediate mortalities. In contrast, the majority of red drum and black drum observed in the release chute were classified as being immediate mortalities or being in poor condition. Gafftopsail catfish in the release chute were mostly assessed as being in good condition. Similar trends were observed with other species in this study, with most individuals being assessed as excellent or good condition in the rollover (Table 3). In the chute bycatch most larger-bodied species were assessed as immediate mortalities or as being in poor condition, while the majority of smaller bodied bycatch species, such as striped mullet (*Mugil cephalus*) or spotted seatrout assessed as being in good condition (Table 4).

Table. 2. The number of fish assessed for condition by at-sea observers in the rollover and chute bycatch for the species used in the survival study.

Source	Species	Number of individuals assessed	%Excellent (n)	%Good/Fair (n)	%Poor (n)	%Mortality (n)
Rollover	Red Drum	666	70.4% (469)	25.5% (170)	1.1% (7)	3.0% (20)
	Black Drum	462	80.7% (373)	14.3% (66)	2.8% (13)	2.2% (10)
	Gafftopsail Catfish	186	45.7% (85)	42.5% (79)	1.6% (3)	10.2% (19)
Chute	Red Drum	681	2.1% (14)	14.5% (99)	22.9% (156)	60.5% (412)
	Black Drum	250	2.8% (7)	29.2% (73)	24.4% (61)	43.6% (109)
	Gafftopsail Catfish	1,622	6.8% (111)	69.2% (1,122)	15.7% (255)	8.3% (134)

Table. 3. Condition scores for bycatch in the rollover bycatch for the most abundant (n>10) species encountered by at-sea observers.

Species	Number of individuals assessed	%Excellent (n)	%Good/Fair (n)	%Poor (n)	%Mortality (n)
Black Drum	462	80.7% (373)	14.3% (66)	2.8% (13)	2.2% (10)
Blacktip Shark	201	14.4% (29)	52.2% (105)	5.5% (11)	27.9% (56)
Blacktip/Spinner Shark	12	33.3% (4)	58.3% (7)	0% (0)	8.4% (1)
Bull Shark	72	33.3% (24)	44.5% (32)	2.8% (2)	19.4% (14)
Carcharhinus sp.	405	19.3% (78)	69.9% (283)	3.2% (13)	7.6% (31)
Cownose Ray	511	61.8% (316)	26.6% (136)	8.4% (43)	3.2% (16)
Crevalle Jack	272	22.1% (60)	48.9% (133)	9.9% (27)	19.1% (52)
Dasyatis sp.	15	66.7% (10)	20% (3)	0% (0)	33.3% (2)
Finetooth Shark	44	36.4% (16)	40.9% (18)	13.6% (6)	9.1% (4)
Gafftopsail Catfish	186	45.7% (85)	42.5% (79)	1.6% (3)	10.2% (19)
Hardhead Catfish	31	74.2% (23)	19.4% (6)	0% (0)	6.4% (2)
Ladyfish	11	27.3% (3)	72.7% (8)	0% (0)	0% (0)
Red Drum	666	70.4% (469)	25.5% (170)	1.1% (7)	3.0% (20)
Spinner Shark	23	13.0% (3)	47.8% (11	4.3% (1)	34.9 (8)
Striped Mullet	60	91.7% (55)	8.3% (5)	0% (0)	0% (0)

Table. 4. Condition scores for large bycatch in the chute bycatch for the most abundant (n>10) species encountered by at-sea observers.

Species	Number of individuals assessed	%Excellent (n)	%Good/Fair (n)	%Poor (n)	%Mortality (n)
Black Drum	250	2.8% (7)	29.2% (73)	24.4% (61)	43.6% (109)
Blacktip Shark	287	0.3% (1)	7% (20)	10.8% (31)	81.9% (235)
Bull Shark	16	0% (0)	0% (0)	18.8% (3)	81.2% (13)
Carcharhinus sp.	15	0% (0)	0% (0)	0% (0)	100% (15)
Cownose Ray	1,019	0.5% (5)	22.9% (233)	47% (479)	29.6% (302)
Crevalle Jack	167	0.6% (1)	4.2% (7)	12.6% (21)	82.6% (138)
Finetooth Shark	114	0.9% (1)	17.5% (20)	20.2% (23)	61.4% (70)
Gafftopsail Catfish	1,622	6.8% (111)	69.2% (1,122)	15.7% (255)	8.3% (134)
Hardhead Catfish	110	8.2% (9)	81.2% (97)	1.8% (2)	1.8% (2)
Red Drum	681	2.1% (14)	14.5% (99)	22.9% (156)	60.5% (412)
Spanish Mackerel	19	5.3% (1)	31.6% (6)	26.3% (5)	36.8% (7)
Spinner Shark	13	0% (0)	0% (0)	15.4% (2)	84.6% (11)
Spotted Seatrout	10	0% (0)	80% (8)	0% (0)	20% (2)
Striped Mullet	244	1.6% (4)	95.9% (234)	0% (0)	2.5% (6)

Fate Estimates

The species-specific sample sizes for each component of the released bycatch held in the survival study each month are shown in Table 5. Table 6 shows the percentage of each species that survived in the ~24-hour holding experiment for each component of the released bycatch. The results are shown both for survival calculated with all fish held in the study (A), and with batches of fish that experienced hypoxia for more than 1 hour removed (B). Fish that were classified as immediate mortalities were not included in the survival study, as their fate was already known. Table 7 shows the final calculated survival after accounting for the proportion of individuals that were classified as immediate mortalities, and applying the survival rates observed in the holding study to the proportion of individuals that were classified as alive.

Table. 5. Total number of fish held by species and month in the ~24-h holding study.

Source	Species	Sample Size by Month							
		Apr	May	Jun	Jul	Aug	Sep	Oct	Total
Rollover	Red Drum	10	31	13	19	32	13	15	133
	Black Drum	6	14	31	0	4	2	2	59
	Gafftopsail Catfish	0	0	1	1	2	3	4	11
	Sum:	**16**	**45**	**45**	**20**	**38**	**18**	**21**	**203**
Chute	Red Drum	0	6	3	1	7	1	2	20
	Black Drum	1	6	16	0	3	0	0	26
	Gafftopsail Catfish	2	5	13	13	11	1	9	54
	Sum:	**3**	**17**	**32**	**14**	**21**	**2**	**11**	**100**

Table. 6. Percent survival of bycatch species tested in the ~24-h holding study calculated using two methods. Method[A]: using all fish in the dataset, including fish temporarily exposed to hypoxia. Method[B]: calculated following the removal of experiments where fish were exposed to hypoxic conditions >1 h in duration within the holding tanks. The ratio of alive to dead fish and the corresponding 95% confidence intervals (CI) are also shown for each method of estimation.

Source	Species	Percent Survival (CI 95%) [A]	Sample size (n) [A]	Percent Survival (CI 95%) [B]	Sample size (n) [B]
Rollover	Red Drum	86.5% (79.5 - 91.8)	133	85.3% (77.3 – 91.4)	109
	Black Drum	89.8% (79.2 – 96.2)	59	94% (83.5 – 98.7)	50
	Gafftopsail Catfish	81.8% (48.2 – 97.7)	11	81.8% (48.2 - 97.7)	11
Chute	Red Drum	5% (0.1 – 24.9)	20	5.9% (0.1 – 28.7)	17
	Black Drum	3.8% (0.1 – 19.6)	26	0% (0.0 – 14.8)	23
	Gafftopsail Catfish	42.6% (29.2 – 56.8)	54	42.2% (27.7 – 57.8)	45

Table. 7. Final estimated percent survival of bycatch species applying the percent survival estimate for each of the two methods to the percentage of fish with condition scores assessed as poor or higher.

Source	Species	Survival Rate (%) [A]	Survival Rate (%) [B]
Rollover	Red Drum	83.91% (77.1 – 89.0)	82.76% (75.0 – 88.7)
	Black Drum	87.82% (77.5 – 94.1)	91.93% (81.7 – 96.5)
	Gafftopsail Catfish	73.46% (43.3 – 87.7)	73.46% (43.3 – 87.7)
Chute	Red Drum	2.0% (0.0 – 9.8)	2.3% (0.0 – 11.3)
	Black Drum	2.1% (0.0 – 11.1)	0% (0.0 – 8.3)
	Gafftopsail Catfish	39.1% (26.8 – 52.1)	38.7% (25.4 – 53.0)

Predictors of Survival

The percent survival and sample size of red drum from the rollover each month are shown in Table 8. Overall survival of red drum in the rollover was high across the season. Some variation in survival was observed between months with lowest rates observed during the month of August (66%) and the highest rates of survival occurring during April, June and October (all 100%). In August, 11 of 32 fish tested from the rollover bycatch resulted in mortalities during the ~24-hr holding study. Ambient readings of dissolved oxygen and sea surface temperature indicated that August was the month with the highest mean sea surface temperatures and lowest mean oxygen levels (Figure 5). When comparing survival outcomes, significant differences were observed for sea surface temperature, dissolved oxygen, pump time, and depth, indicating that environmental conditions influenced survival for the few rollover fish that were mortalities (Figure 6).

Table. 8. Percent survival by month for red drum from the rollover tested in the ~24-h holding study. Note that other species are not include due to low monthly sample sizes.

Species		Percent Survival by Month[A]						
		Apr	May	Jun	Jul	Aug	Sep	Oct
Red Drum	%Survival	100%	87%	100%	95%	66%	85%	100%
	Sample Size	10	31	13	19	32	13	15

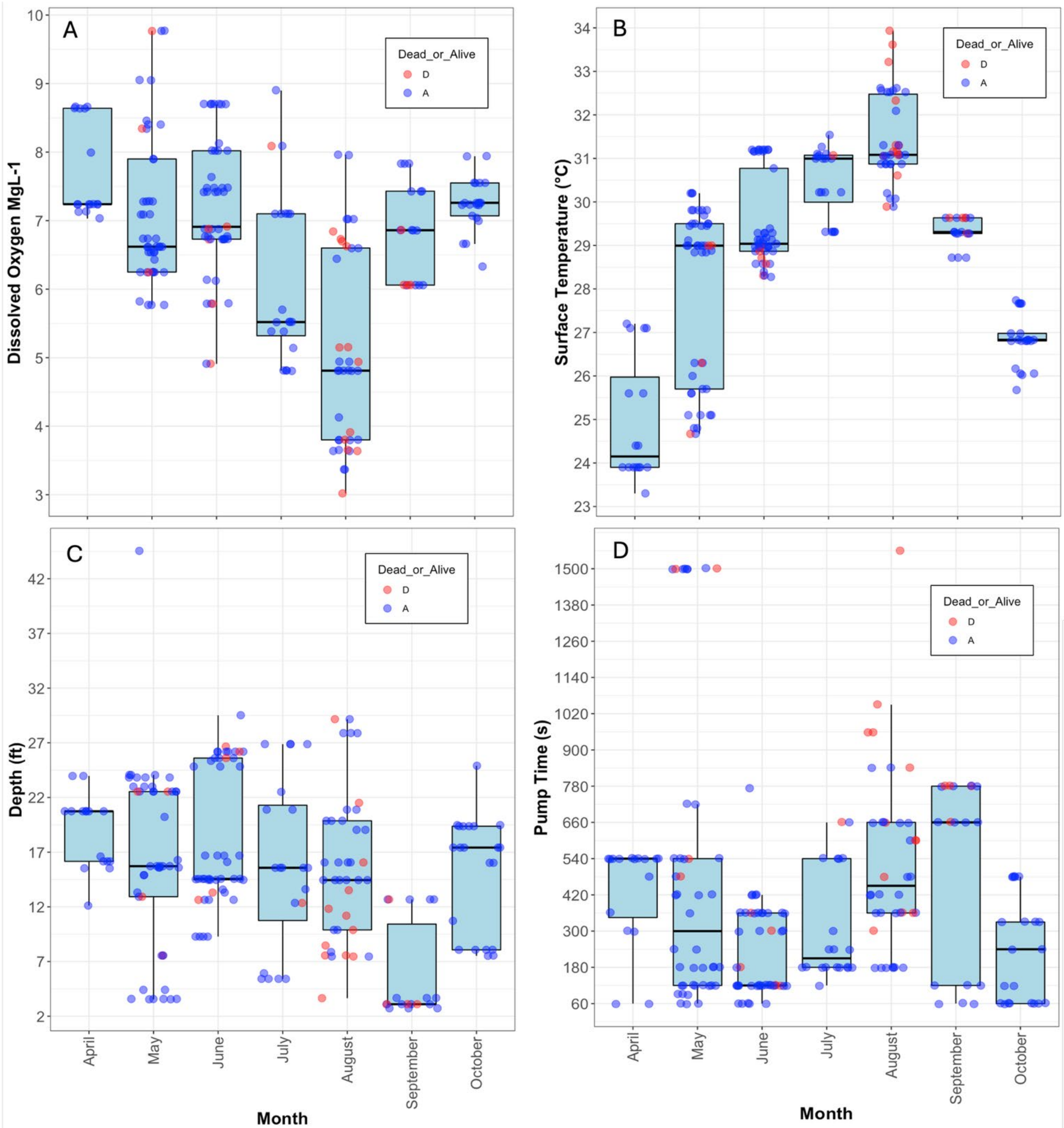


Figure 5. Monthly variation in (A) surface dissolved oxygen (DO MgL^{-1}); (B) sea surface temperature (°C); (C) set depth (ft); and (D) pump time (s) for sets from which rollover survival fish were sampled. The horizontal line on the boxplots indicates the median and the boxes the interquartile range. Data points overlayed are for all rollover bycatch tested in the survival study, colors indicate the fate of individuals from the holding study ('D' = mortality/dead and 'A' = alive/survived).

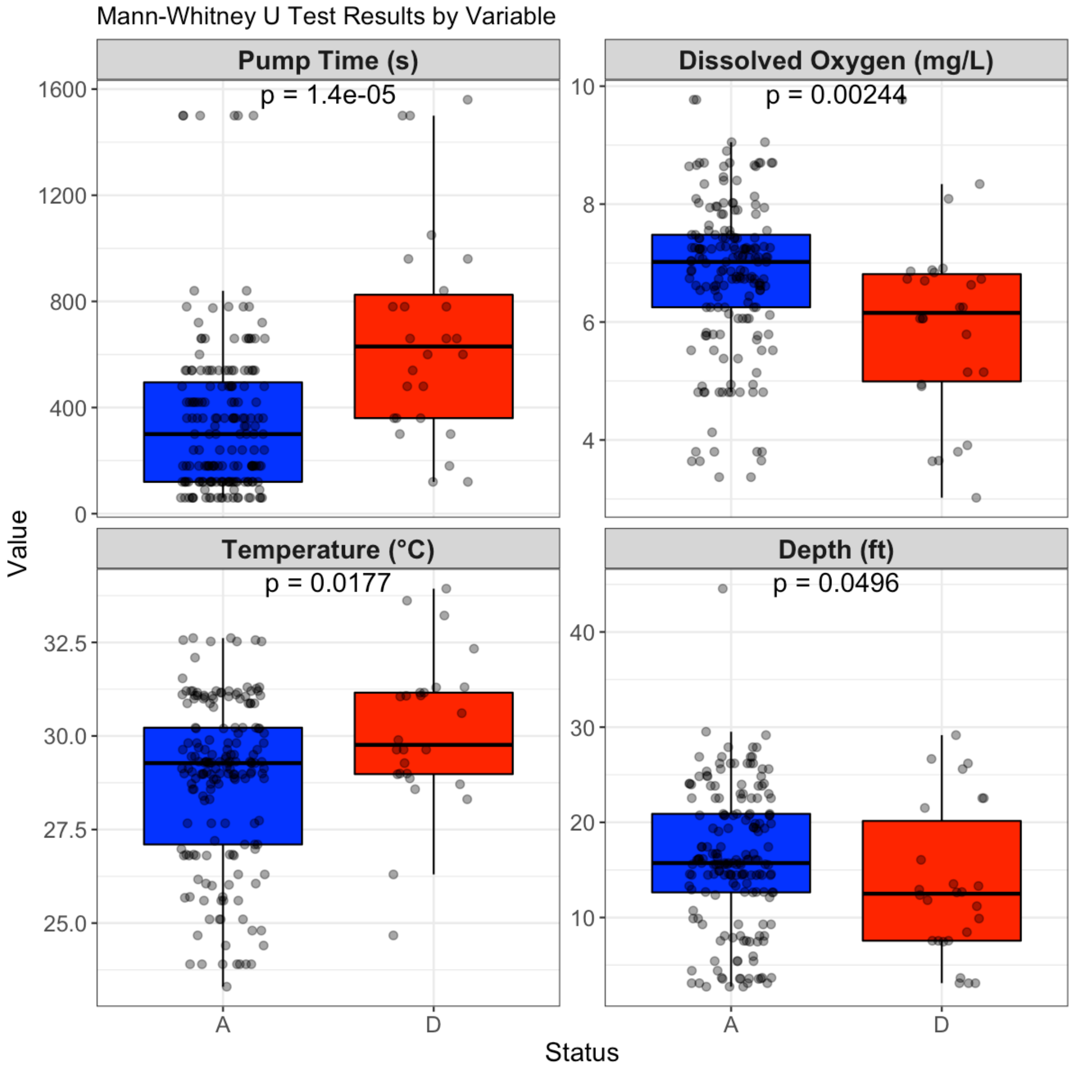


Figure 6. Comparison of environmental and set variables between survival outcomes for rollover fish. Boxplots show distributions of pump time (top left), dissolved oxygen (top right), sea surface temperature (bottom left), and depth (bottom right) grouped by survival status. P-values from Mann-Whitney U tests are show in each panel. Significant differences were observed for all four variables, indicating that environmental and set conditions influenced survival outcome.

Table. 9. Likelihood values and Akaike metrics for the logistic regression models that account for >99% of the weight (out of the 31 models) for red drum in the rollover. Abbreviations are as follows: k = the number of model parameters; AICc = the small sample size corrected value of the Akaike information criterion (a lower value indicates a better fit); ∆AICc = the AICc value in question – the lowest AICc value of all 31 models; W_i = the Akaike weight, interpreted as the direct probability of that model being's true given the suite of models investigated. Dep = set depth in meters; Pump = pump time in seconds; Temp = surface temperature in degrees C; DO = surface Dissolved Oxygen in MgL^{-1}, and TL = Total Length (mm).

Model Term											
Rank	Pump	Dep	Temp	DO	TL	Log-likelihood	k	%Dev	AICc	∆AICc	W_i
1	X	X	X			-35.63	4	0.32	79.57	0.00	0.48
2	X	X	X		X	-34.94	5	0.33	81.28	1.71	0.20
3	X	X	X	X		-34.09	5	0.32	81.66	2.10	0.17
4	X	X	X	X	X	-35.40	6	0.33	83.47	3.90	0.07
5	X	X				-35.42	3	0.25	84.98	5.41	0.03
6	X	X		X		-34.80	4	0.26	85.88	6.31	0.02
7	X	X			X	-34.02	4	0.25	86.95	7.38	0.01
8	X	X		X	X	-35.20	5	0.27	87.55	7.98	0.01
9	X		X			-38.12	3	0.22	88.91	9.34	0.00
10	X		X		X	-39.40	4	0.23	90.00	10.44	0.00

The model diagnostics for the rollover red drum in the holding study showed that the top-ranked logistic model (e.g., lowest AICc) fit the data well (Appendix 1). The uniformity test (one-sample Kolmogorov–Smirnov test) showed no deviation from the expected uniform distribution of residuals (D = 0.030, $p = 0.99$), indicating no evidence of misspecification in the model structure. Similarly, the dispersion test revealed no signs of overdispersion in the residuals (dispersion = 0.952, $p = 0.774$), suggesting that the variance in the observed data was well-captured by the model (a value of 1.00 would indicate no overdispersion). The zero-inflation test, which compares the number of observed versus expected zero outcomes under the fitted model, also showed no evidence of excess zeros (ratioObsSim = 1.001, $p = 1$), confirming that the model adequately accounted for the binary nature of the response.

Given the GLM with a binomial family and logit link function was a suitable model for the rollover red drum survival data, the top 10 models accounted for >99% of the weight (Table 9). Overall, there was a high probability that depth, pump time and sea surface temperature are important terms in describing red drum survival, with the top 4 models including all three of these terms and accounting for 95% of the total weight (Table 10). The top-ranked GLM (48% of weight) describing survival included set temperature, pump time, and depth as linear predictors. All three covariates were statistically significant (Table 11). Specifically, set temperature was negatively associated with survival (Estimate = –0.4098, $p = 0.016$), indicating reduced survival at higher temperatures. Pump time also exhibited a negative effect (Estimate = –0.0031, $p < 0.001$), suggesting that longer soak times reduced the likelihood of survival. In contrast, depth was positively associated with survival (Estimate = 0.1398, $p = 0.002$), implying improved survival in deeper water. The model explained approximately 32.4% of the deviance. To evaluate the classification performance of the top-ranked logistic generalized linear model, we generated a Receiver Operating Characteristic (ROC) curve using predicted survival probabilities from the model. The ROC curve plots the true positive rate (sensitivity) against the false positive rate (1 − specificity) across a range of thresholds. The area under the ROC curve (AUC) was 0.867, indicating that the model had high discriminative ability to distinguish between survival and non-survival outcomes (an AUC of 0.5 corresponds to no discriminative ability).

Table. 10. Weight of evidence (Akaike weight, W_i) of model terms for the 31 models. W_i was summed across the number of models with each term versus the number of models without each term to estimate the percent chance that each term was important.

	% Chance that term is	
Model Term	Important	Unimportant
Dep	99	1.2
Pump	99.9	0.1
Temp	92.6	7.1
DO	26.7	73.3
TL	29.6	70.4

Table. 11. Top-ranked modelled effects of predictors on the odds of survival for rollover red drum (n=133). Likelihood ratio tests (LRT), comparing the full model to an intercept-only model were conducted to determine overall model significance.

Species	Term	Coefficient	SE	Z value	Pr(>|z|)
Red Drum Rollover ($X^2_{(3,129)}$=34.19, p<0.001)	Temp	-0.4098359	0.1706344	-2.402	P <0.05
	Pump	-0.0030582	0.0007978	-3.833	P <0.001
	Depth	0.1397816	0.0461978	3.026	P <0.01

Reflex Score Relationships

RAMP scores for fish in the rollover bycatch component were generally low and indicated little to no reflex impairment (Table 6). For instance, 93.2% of red drum, 96.7% of black drum, and 90.9% of gafftopsail catfish from the rollover bycatch that were tested in the ~24-h holding study were assigned a RAMP score between 0 and 0.2 (e.g., 0 to 1 reflexes impaired) at the start of the holding study (Table 6). Rollover fish with low RAMP scores exhibited high survival rates (Figure 7). Of the 6 reflexes assessed, the orientation reflex was most commonly impaired in rollover fish, with 12.8% of red drum, 11.7% of black drum, and 9.1% of gafftopsail catfish failing to right themselves within ~3 seconds of release, although we note that fish appeared to recover quickly shortly after (Table 12), in line with the high rollover bycatch survival observed (Table 4 & 5). Sample sizes of fish with RAMP scores >0.4 were limited for fish in the rollover bycatch component (Figure 7).

For the chute bycatch, where survival was generally low (Table 4 & 5) RAMP scores were correspondingly high, with 50% of red drum and 74% of black drum being assigned ramp scores of 0.4 or higher (e.g., 2 or more reflexes impaired). Survival for red drum and black drum in the holding study was low, consisting of a single black drum and red drum surviving the holding period across all experiments (Table 4). Gafftopsail catfish survival in the chute bycatch was markedly higher than that observed with drum, with only 31% of gafftopsail catfish being assigned RAMP scores of 0.4 or higher. Gafftopsail catfish with RAMP scores of 0, 0.2, and 0.4 corresponded to a 50%, 35%, and 44% chance of survival in the holding study, respectively (Figure 7).

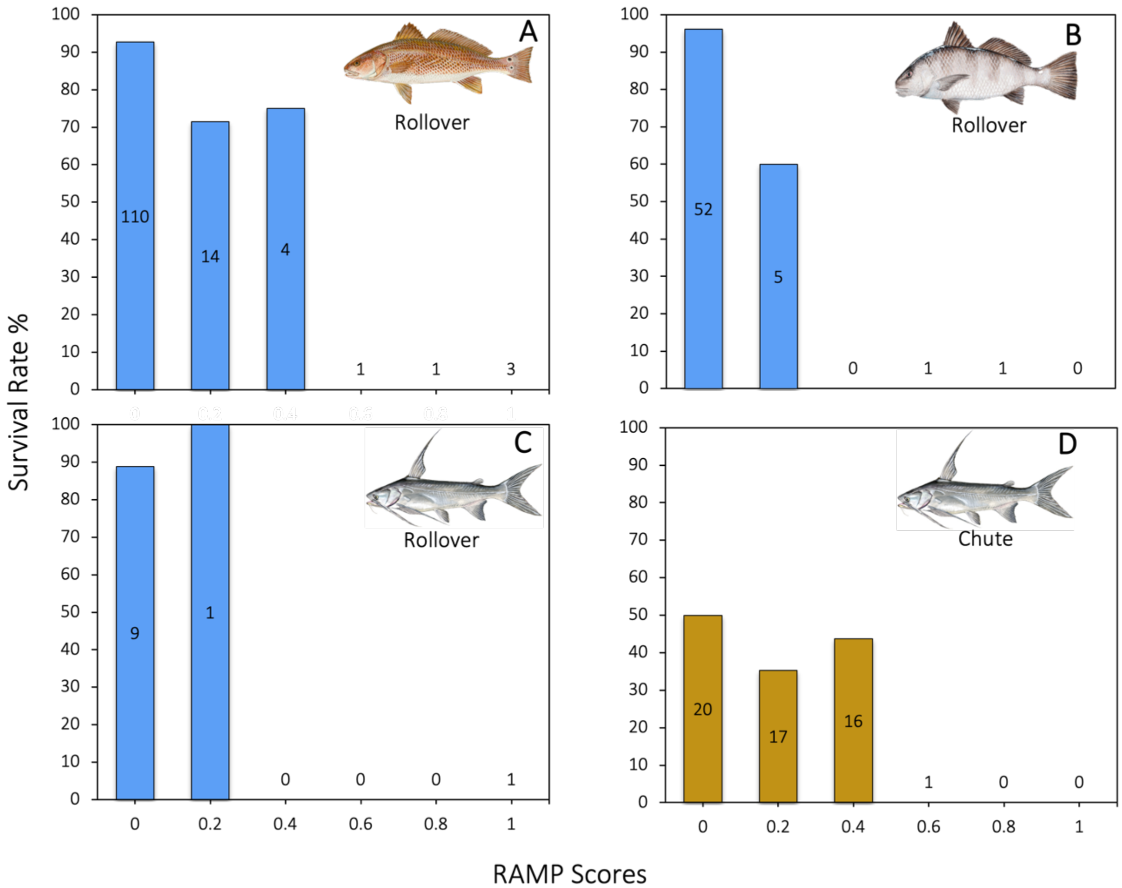


Figure 7. Survival rates within each assigned RAMP score determination by species and released bycatch source. (A) Red drum from the rollover bycatch (B) Black drum from the rollover bycatch (C) Gafftopsail catfish from the rollover bycatch (D) Gafftopsail catfish from the chute bycatch. The numbers by each bar represent the total number of fish assigned each RAMP score. Higher RAMP scores denote fish with more extreme levels of reflex impairment. Red drum and black drum from the chute bycatch, where overall survival was exceedingly low irrespective of the assigned RAMP scores, are not shown. Each increment of 0.2 represents an impaired reflex, with a value of 1 denoting that all reflexes were impaired, and 0 denoting a healthy fish with all reflexes unimpaired.

Table. 12. Mean RAMP scores for fish with reflexes assessed at the start and end of the ~24-h holding study. Each increment of 0.2 represents an impaired reflex, with a value of 1 denoting that all reflexes were impaired, and 0 denoting a healthy fish with all reflexes unimpaired.

Source	Species	Mean Start RAMP	Mean End RAMP
Rollover	Red Drum	0.07	0.00
	Black Drum	0.04	0.01
	Gafftopsail Catfish	0.11	0.09
Chute	Red Drum	0.37	1
	Black Drum	0.43	0
	Gafftopsail Catfish	0.19	0.16

Table. 13. Impairment of individual reflexes by species and bycatch component. Values represent the proportion of individuals within each respective reflex impairment at the start of the holding period. Total sample sizes are given in parentheses. Each increment of 0.2 represents an impaired reflex, with a value of 1 denoting that all reflexes were impaired, and 0 denoting a healthy fish with all reflexes unimpaired. VOR = Vestibular-Ocular Response.

Source	Species	Tail Grab	Body Flex	Head Complex	VOR	Orientation
Rollover	Red Drum	0.08 (11)	0.07 (9)	0.02 (3)	0.03 (4)	0.13 (17)
	Black Drum	0.03 (2)	0.03 (2)	0.02 (1)	0 (0)	0.12 (7)
	Gafftopsail Catfish	0.09 (1)	0.09 (1)	0.09 (1)	0.18 (2)	0.09 (1)
Chute	Red Drum	0.35 (7)	0.15 (3)	0.3 (6)	0.4 (8)	0.65 (13)
	Black Drum	0.30 (8)	0.22 (6)	0.30 (8)	0.63 (17)	0.74 (20)
	Gafftopsail Catfish	0.35 (19)	0.07 (4)	0 (0)	0.22 (12)	0.31 (17)

Released Fish

A total of 116 red drum, 54 black drum, and 32 gafftopsail catfish were released with conventional tags during the study period. At the time of release, one red drum and two black drum had shed one of their two tags, but all fish had at least one tag remaining after 24 hours. One red drum sampled from the rollover on September 23rd, 2024 was returned by a fisher 32 days after it was released on October 26th, 2024. This individual was recaptured near Red Pass, Louisiana, approximately 9 miles east of the location in West Bay where it was originally sampled by observers. The individual was reported to be healthy by the angler, demonstrating that longer-term survival is possible with red drum from the rollover bycatch. Fish released from the rollover were generally vigorous, had unimpaired reflexes (Table 6), and showed no indications that released individuals would result in mortalities shortly after release. By contrast, the single red drum to survive from the chute bycatch was highly impaired (RAMP = 1) and was borderline moribund at the time of release. Of the 23 gafftopsail catfish released from the chute bycatch, four individuals (17%) showed late-stage signs of corneal cloudiness, a common disorder likely resulting from capture and confinement stress. These individuals received impaired vestibular-ocular response scores. The single black drum to survive and be released from the chute bycatch appeared to recover well in the holding study, exhibiting no impaired reflexes at the time of release (Table 6).

Discussion

The present study demonstrates that discard mortality in the Gulf menhaden purse seine fishery varies considerably between fish released directly from the net in the rollover procedure and fish released via the excluder grate and release chute. Results of the ~24-h holding study, when accounting for fish assessed as immediate mortalities at sea (Table 7), indicate that overall survival of fish within the rollover bycatch (e.g., individuals that never travelled through the vessel's on board fish pump) is high, with estimates of 84% survival for red drum, 88% survival for black drum, and 73% survival for gafftopsail catfish. By contrast, fish evaluated from the chute bycatch (e.g., fish that travelled through the vessel's fish pump before release), demonstrated markedly lower survival rates, with survival estimated at 2% for red drum, 2% for black drum, and 39% for gafftopsail catfish. RAMP scores similarly indicated higher levels of impairment for chute fish and lower levels of impairment and higher recovery rates for rollover fish. Condition scores for discarded species that were not tested in the holding study again indicated higher levels of immediate mortality or poor condition fish in the chute bycatch relative to that of the rollover bycatch (Tables 3 and 4).

No previous studies have experimentally investigated post-release mortality within the Gulf or Atlantic menhaden purse seine fisheries. However, a small number of at-sea observer programs have been conducted over the last half century, and in a few cases, observers have inferred survival based on visual assessment of bycatch fates (Condry, 1994; De silva, 1998; Pulver and Scott-Denton, 2012). De Silva (1998) and Pulver & Scott Denton (2012) report that 50-58% of red drum were released dead at sea, with the remaining fish being released disoriented. Condrey (1994) reported that 20% of red drum (n=15) and 47% of gafftopsail catfish were released dead at sea. De Silva et al. (2001) estimated that 75% of sharks encountered in the fishery are released dead at sea. Direct comparison to these studies is difficult for several reasons. First, survival estimates produced generally do not differentiate bycatch released by the large fish excluder grate from bycatch rolled out of the net. Second, visual assessment at the time of release does not directly equate to survival. Fish that appear to be in good condition at the time of release may still suffer mortality. Third, changes in gear and fishing methods have occurred within the industry over the last few decades that could alter survival. Historically some release chutes in the fishery directed chute bycatch to the deck of the vessel for sorting prior to release. Finally, in 2024 a half mile exclusion zone was imposed along the coast of Louisiana preventing fishing in some shallower areas (LDWF, 2024b).

Lower survival of chute fish that pass through the onboard fish pump and then travel in air down the release chute is perhaps not surprising. Mechanical injury and death of fish that pass through manmade pumping structures is a well-known phenomenon in freshwater ecosystems worldwide, with injury typically caused by strikes of the impeller's leading edge, pressure reduction, or shear force (Neitzel et al., 2000; Pan et al., 2022; Turnpenny et al., 1992). In line with this, a high percentage of chute fish were classified as immediate mortalities having lost tails, been decapitated, or having lost internal organs presumably due to contact with the impeller or changes in pressure during passage. Recent studies have demonstrated that survival of fish through pump systems can be species and size specific, with larger species generally exhibiting lower survival percentages after passage through some pump systems (Baumgartner et al., 2009; Raoult et al., 2019; Thompson et al., 2011). Larger fish are generally more resistant to shear forces and are more susceptible to physical strike by impellers (McNabb et al., 2003). By contrast, smaller fish have reduced swimming abilities and are more prone to the effects of sudden pressure changes, but are less susceptible to physical strike (Neitzel et al., 2004). In our study, this assertion may be supported by the increased survival of gafftopsail catfish (mean TL: 504 mm) in the chute bycatch where 92% of fish passed through the pump system without sustaining major external injuries, compared to just 40% for red drum (mean TL: 904 mm), and 17% for crevalle jack (mean TL: 1002 mm). Other factors that likely reduced the chances of survival for the chute bycatch include physical trauma caused by fish hitting the large fish excluder grate with force, and the increased air exposure times as fish travel down the release chute. Indeed, air exposure is a well-recognized stressor known to increase bycatch mortality in Pacific halibut (*Hippoglossus stenolepis*), lingcod (*Ophiodon elongatus*) (Davis and Olla, 2002), and sablefish (*Anoplopoma fimbria*) (Davis and Parker, 2004) captured in commercial fisheries.

Survival of red drum in the rollover appeared to be linked to pump time (a proxy for set size and thus soak time), depth, and sea surface temperature. Numerous studies have found that environmental conditions can alter post-release mortality rates of bycatch (Gale et al., 2013; Weltersbach and Strehlow, 2013). In the present study, while red drum survival in the rollover bycatch was generally high, we observed variation in survival estimates between months. April and October experienced the highest rates of survival with 100% of rollover red drum tested in the holding study surviving. By contrast, survival for the months of August and September dropped to 66% and 85%, respectively. It is widely recognized for many species that higher water temperatures exacerbate the effects of capture on released fish (Gale et al., 2013). Our observation of reduced survival during warmer months is consistent with previous findings in marine fisheries. For instance, Davis and Parker (2004) demonstrate that warmer water temperatures are important predictors of increased mortality for five species of sharks caught in the GoA bottom long-line fishery. More recently, Capizzano et al. (2019) found that water temperature was a compelling and potentially sole mortality contributor for Haddock (*Melanogrammus aeglefinus*) discarded in a recreational fishery. For the Gulf menhaden reduction fishery, multiple conditions appear to contribute to post-release mortality, with large sets made in shallow warm water yielding the lowest survival for red drum in the rollover. However, due to the relatively low sample sizes available in the survival study, and because reliable depth and temperature data were not available for non-sampled sets in the fishery, we did not attempt to model the effects of these variables on the overall survival of red drum in the fishery.

With respect to condition scores, not all released species fared equally well in the rollover bycatch. For instance, 35% of spinner sharks, 28% of blacktip sharks, and 19% of bull sharks within the purse net were determined mortalities prior to release. Sharks that exhibit ram ventilation rely in part on increasing swimming speed to compensate for decreases in oxygen availability (Carlson and Parsons, 2001; Manire et al., 2001). Such behaviors are generally not possible when confined within the purse net full of catch. Of note is that several studies have demonstrated that when these obligate ram ventilators are caught, asphyxiation can set in relatively rapidly under some conditions (Dapp et al., 2017; Ellis et al., 2017). Factors such as soak time , increased water temperatures (Morgan and Burgess, 2007) and hypoxia (Carlson and Parsons, 2001) have all been shown to increase shark mortalities, and likely contributed to the mortalities observed as part of this study. Anecdotally, our observers witnessed high shark mortalities in a large set where soak time surpassed 3 hours. While all the sharks captured in this set died before the rollover procedure, non-ram ventilating species such as Atlantic croaker and red drum were observed swimming above the dead menhaden and sharks even after hours of confinement. Similar to ram-ventilating sharks, some fast, continuously-swimming teleost's have increased metabolic demands and rely on forward momentum to drive ventilatory water across the gills (Sanderson et al., 1996; Wegner et al., 2010). These considerations likely explain the higher rollover bycatch mortalities for crevalle jack (19%), an active pelagic swimmer, than that of estuarine-dependent red drum (2%) that are more tolerant of hypoxic conditions (Pan et al., 2016). While this study demonstrates that over 80% of blacktip shark, bull shark, and spinner shark in the chute bycatch are released dead, the post-release survival of the ~70% of sharks released in the rollover bycatch (e.g., non-mortalities) at sea is not known. Additional investigation such as telemetry studies (Ellis et al., 2017) are needed to determine the delayed mortality rates for elasmobranch species incidentally caught in menhaden purse seine nets, as well as for teleost species not tested as part of our holding study.

While holding studies have been widely used to estimate post-release mortality, they are not without limitation. Trade-offs for short-term fish retention include protection against predation (upward bias), increased handling (downward bias), and induced stress from prolonged confinement (downward bias) (Schweitzer et al., 2020). Fish housed in our holding tanks were sheltered from predation and predator evasion inevitably biased survival estimates higher. Little is known, however, about post-release predation rates in the menhaden purse seine fishery and for most fisheries worldwide (Raby et al., 2015). The large body size of the released bycatch within the Gulf menhaden fishery likely limits the number of predators capable of consuming such large individuals. Therefore, we expect post-release predation, and the bias in our survival estimates caused by protecting fish in the holding study from predation, to be low. While fish from the chute bycatch experienced higher levels of impairment and may therefore be more susceptible to predation, we suspect this consideration is likely negated by the overall low survival of fish in the chute bycatch (2% - 39%). Holding studies in other fisheries have investigated the effects of handling and confinement stress via the inclusion of control fish handled with gear believe to be innocuous, and by varying holding durations (Gutowsky et al., 2015). True controls, however, are nearly impossible to obtain as experimentation almost always involves some degree of handling and stress (Rogers et al., 2014). In this study, the high percentage of fish that survived from the rollover bycatch would imply that any effects of handling and confinement stress were likely minimal. While we cannot rule out the contribution of induced stress to the lower survival of chute fish, the low RAMP scores and high number of moribund fish assessed in the chute bycatch would strongly imply that capture in the fishery had the strongest influence on survival and not experimentation. Indeed, extreme care was taken to minimize handling times and the ~24-h confinement period was chosen to be consistent with previous studies in purse seine fisheries in order to accurately assess survival without prolonging confinement (Raby et al., 2015). While future biotelemetry studies might provide additional insight into survival and depredation rates in the absence of confinement stress, tagging studies pose a different set of issues, including the inability to physically verify the fate of released fish (Brownscombe et al., 2019). These studies, however, may be the most appropriate means of investigating post-release survival for elasmobranchs and other taxa generally not suitable for holding studies.

Our finding that high survival of red drum, black drum and gafftopsail catfish occurs in the rollover bycatch and that survival of these same species is low in the chute bycatch, has important practical implications. Total survival of released bycatch can be increased if fish are released in the rollover procedure rather than the release chute. Modifications to hose cage designs that more effectively exclude large bycatch from entering the vessels fish pump represent a fruitful avenue for reducing retention and mortality of large bycatch in the fishery. Future investigation is needed to evaluate the optimal bycatch excluder design to meet both conservation goals and practical constraints within the fishery.

Citations

Ackerly, K.L., Esbaugh, A.J., 2020. The additive effects of oil exposure and hypoxia on aerobic performance in red drum (Sciaenops ocellatus). Sci. Total Environ. 737, 140174. https://doi.org/10.1016/j.scitotenv.2020.140174

Ackerly, K.L., Negrete, B., Dichiera, A.M., Esbaugh, A.J., 2023. Hypoxia acclimation improves mitochondrial efficiency in the aerobic swimming muscle of red drum (Sciaenops ocellatus). Comp. Biochem. Physiol. A. Mol. Integr. Physiol. 282, 111443. https://doi.org/10.1016/j.cbpa.2023.111443

Alverson, D.L., Freeberg, M.H., Murawski, S.A., Pope, J.G., 1996. A global assesment of fisheries bycatch and discards, 339th ed. FAO Fisheries Technical Paper.

Baker, S.M., Reyier, E.A., Ahr, B.J., Cook, G.S., 2023. Assessing the effects of physical barriers and hypoxia on red drum movement patterns to develop more effective management strategies. Fishes 8, 171. https://doi.org/10.3390/fishes8040171

Baumgartner, L.J., Reynoldson, N.K., Cameron, L., Stanger, J.G., 2009. Effects of irrigation pumps on riverine fish. Fish. Manag. Ecol. 16, 429–437. https://doi.org/10.1111/j.1365-2400.2009.00693.x

Benoît, H.P., Hurlbut, T., Chassé, J., 2010. Assessing the factors influencing discard mortality of demersal fishes using a semi-quantitative indicator of survival potential. Fish. Res. 106, 436–447. https://doi.org/10.1016/j.fishres.2010.09.018

Benoît, H.P., Hurlbut, T., Chassé, J., Jonsen, I.D., 2012. Estimating fishery-scale rates of discard mortality using conditional reasoning. Fish. Res. 125–126, 318–330. https://doi.org/10.1016/j.fishres.2011.12.004

Benoît, H.P., Kneebone, J., Tracey, S.R., Bernal, D., Hartmann, K., Golet, W., 2020. Distinguishing discard mortality from natural mortality in field experiments based on electronic tagging. Fish. Res. 230, 105642. https://doi.org/10.1016/j.fishres.2020.105642

Brownscombe, J.W., Lédée, E.J.I., Raby, G.D., Struthers, D.P., Gutowsky, L.F.G., Nguyen, V.M., Young, N., Stokesbury, M.J.W., Holbrook, C.M., Brenden, T.O., Vandergoot, C.S., Murchie, K.J., Whoriskey, K., Mills Flemming, J., Kessel, S.T., Krueger, C.C., Cooke, S.J., 2019. Conducting and interpreting fish telemetry studies: considerations for researchers and resource managers. Rev. Fish Biol. Fish. 29, 369–400. https://doi.org/10.1007/s11160-019-09560-4

Burnham K. P., and Anderson D. R., 2002. Model selection and multimodel inference: A practical information-theoretic approach 2nd edition.

Campbell, M.D., Patino, R., Tolan, J., Strauss, R., Diamond, S.L., 2010. Sublethal effects of catch-and-release fishing: measuring capture stress, fish impairment, and predation risk using a condition index. ICES J. Mar. Sci. 67, 513–521. https://doi.org/10.1093/icesjms/fsp255

Capizzano, C.W., Zemeckis, D.R., Hoffman, W.S., Benoît, H.P., Jones, E., Dean, M.J., Ribblett, N., Sulikowski, J.A., Mandelman, J.W., 2019. Fishery-Scale siscard mortality rate estimate for haddock in the Gulf of Maine recreational fishery. North Am. J. Fish. Manag. 39, 964–979. https://doi.org/10.1002/nafm.10328

Carlson, J.K., Parsons, G.R., 2001. The effects of hypoxia on three sympatric shark species: physiological and behavioral responses. Environ. Biol. Fishes 61, 427–433. https://doi.org/10.1023/A:1011641302048

Clopper, C.J., Pearson, E.S., 1934. The use of confidence or fiducial limits illustrated in the case of the binomial. Biometrika 26, 404–413. https://doi.org/10.1093/biomet/26.4.404

Coggins, L.G., Catalano, M.J., Allen, M.S., Pine, W.E., Walters, C.J., 2007. Effects of cryptic mortality and the hidden costs of using length limits in fishery management. Fish Fish. 8, 196–210. https://doi.org/10.1111/j.1467-2679.2007.00247.x

Colotelo, A.H., Raby, G.D., Hasler, C.T., Haxton, T.J., Smokorowski, K.E., Blouin-Demers, G., Cooke, S.J., 2013. Northern pike bycatch in an inland commercial hoop net fishery: Effects of water temperature and net tending frequency on injury, physiology, and survival. Fish. Res. 137, 41–49. https://doi.org/10.1016/j.fishres.2012.08.019

Condry, R., 1994. Bycatch in the U.S. Gulf of Mexico menhaden fishery. Results of onboard sampling conducted in the 1992 fishing season.

Cook, K.V., Hinch, S.G., Watson, M.S., Patterson, D.A., Reid, A.J., Cooke, S.J., 2018. Experimental capture and handling of chum salmon reveal thresholds in injury, impairment, and physiology: Best practices to improve bycatch survival in a purse seine fishery. Fish. Res. 206, 96–108. https://doi.org/10.1016/j.fishres.2018.04.021

Dapp, D.R., Huveneers, C., Walker, T.I., Reina, R.D., 2017. Physiological response and immediate mortality of gill-net-caught blacktip reef sharks (Carcharhinus melanopterus). Mar. Freshw. Res. 68, 1734–1740. https://doi.org/10.1071/MF16132

Davis, M.W., 2010. Fish stress and mortality can be predicted using reflex impairment. Fish Fish. 11, 1–11. https://doi.org/10.1111/j.1467-2979.2009.00331.x

Davis, M.W., 2007. Simulated fishing experiments for predicting delayed mortality rates using reflex impairment in restrained fish. ICES J. Mar. Sci. 64, 1535–1542. https://doi.org/10.1093/icesjms/fsm087

Davis, M.W., Olla, B.L., 2002. Mortality of lingcod towed in a aet as related to fish length, seawater temperature, and air exposure: A laboratory bycatch study. North Am. J. Fish. Manag. 22, 1095–1104. https://doi.org/10.1577/1548-8675(2002)022<1095:MOLTIA>2.0.CO;2

Davis, M.W., Parker, S.J., 2004. Fish size and exposure to air: Potential effects on behavioral impairment and mortality rates in discarded sablefish. North Am. J. Fish. Manag. 24, 518–524. https://doi.org/10.1577/M03-030.1

De silva, J., 1998. The nature and extent of species interactions with the United States gulf menhaden fishery. LSU Hist. Diss. Theses. https://doi.org/10.31390/gradschool_disstheses.6821

De Silva, J., 1998. The Nature and Extent of Species Interactions With the United States Gulf Menhaden Fishery. (Doctor of Philosophy). Louisiana State University and Agricultural & Mechanical College. https://doi.org/10.31390/gradschool_disstheses.6821

De Silva, J.A., Condrey, R.E., Thompson, B.A., 2001. Profile of shark bycatch in the U.S. Gulf of Mexico menhaden fishery. North Am. J. Fish. Manag. 21, 111–124. https://doi.org/10.1577/1548-8675(2001)021<0111:POSBIT>2.0.CO;2

Dormann, C.F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, G., Marquéz, J.R.G., Gruber, B., Lafourcade, B., Leitão, P.J., Münkemüller, T., McClean, C., Osborne, P.E., Reineking, B., Schröder, B., Skidmore, A.K., Zurell, D., Lautenbach, S., 2013. Collinearity: a review of methods to deal with it and a simulation study evaluating their performance. Ecography 36, 27–46. https://doi.org/10.1111/j.1600-0587.2012.07348.x

Ellis, J.R., McCully Phillips, S.R., Poisson, F., 2017. A review of capture and post-release mortality of elasmobranchs. J. Fish Biol. 90, 653–722. https://doi.org/10.1111/jfb.13197

Eskelund, M., Methling, C., Madsen, N., 2019. Survival of discarded plaice (Pleuronectes platessa) from Norway lobster (Nephrops norvegicus) otter-trawl fishery. J. Appl. Ichthyol. 35, 645–654. https://doi.org/10.1111/jai.13888

Gale, M.K., Hinch, S.G., Donaldson, M.R., 2013. The role of temperature in the capture and release of fish. Fish Fish. 14, 1–33. https://doi.org/10.1111/j.1467-2979.2011.00441.x

GSMFC, 2015. The gulf menhaden fishery of the Gulf of Mexico: A regional management plan (Technical Report No. 240).

Guillory, V., Hutton, G., 1982. A survey of bycatch in the Lousiana gulf menhaden fishery. Proc Annu Conf Southeast Assoc Fish Wildl Agencies 36, 213–223.

Gutowsky, L.F.G., Aslam, W., Banisaeed, R., Bell, L.R., Bove, K.L., Brownscombe, J.W., Burrows, G.J.J., Chu, E., Magel, J.M.T., Rous, A.M., Cooke, S.J., 2015. Considerations for the design and interpretation of fishing release mortality estimates. Fish. Res. 167, 64–70. https://doi.org/10.1016/j.fishres.2015.02.002

Harrington, J.M., Myers, R.A., Rosenberg, A.A., 2005. Wasted fishery resources: discarded by-catch in the USA. Fish Fish. 6, 350–361. https://doi.org/10.1111/j.1467-2979.2005.00201.x

Jennings, S., Kaiser, M.J., 1998. The effects of fishing on marine ecosystems, in: Blaxter, J.H.S., Southward, A.J., Tyler, P.A. (Eds.), Advances in Marine Biology. Academic Press, pp. 201–352. https://doi.org/10.1016/S0065-2881(08)60212-6

Kaimmer, S.M., Trumble, R.J., 1998. Injury, condition, and mortality of Pacific halibut bycatch following careful release by Pacific cod and sablefish longline fisheries. Fish. Res. 38, 131–144. https://doi.org/10.1016/S0165-7836(98)00153-2

LDWF, 2024a. Estimates of spotted seatrout and red drum bycatch in the Louisiana menhaden reduction fishery. Tech. Memo.

LDWF, 2024b. Establishing the 2024 commercial menhaden season and associated regulations: Declaration of emergency. Tech. Rep.

Manire, C., Hueter, R., Hull, E., Spieler, R., 2001. Serological changes associated with gill-net capture and restraint in three species of sharks. Trans. Am. Fish. Soc. 130, 1038–1048. https://doi.org/10.1577/1548-8659(2001)130<1038:SCAWGN>2.0.CO;2

McNabb, C.D., Liston, C.R., Borthwick, S.M., 2003. Passage of juvenile chinook salmon and other fish species through archimedes lifts and a hidrostal pump at Red Bluff, California. Trans. Am. Fish. Soc. 132, 326–334. https://doi.org/10.1577/1548-8659(2003)132<0326:POJCSA>2.0.CO;2

Morgan, A., Burgess, G.H., 2007. At-Vessel fishing mortality for six species of sharks caught in the Northwest Atlantic and Gulf of Mexico. Gulf Caribb. Res. 19. https://doi.org/10.18785/gcr.1902.15

Muir, J.A., Barker, R.J., Hutchinson, M.R., Leroy, B.M., Nicol, S.J., Scutt Phillips, J., 2022. Estimating post-release mortality of long-line caught tropical tunas in the Pacific Ocean. Fish. Res. 249, 106194. https://doi.org/10.1016/j.fishres.2021.106194

Neilson, J.D., Busawon, D.S., Andrushchennko, I.V., Campana, S.E., Carruthers, E.H., Harris, L.E., Stokesbury, M., 2012. A review of approaches to assess survival of released catch from Canadian large pelagic longline fisheries. Canada Department of Fisheries and Oceans, p. 39.

Neitzel, D.A., Dauble ,D. D., Čada ,G. F., Richmond ,M. C., Guensch ,G. R., Mueller ,R. P., Abernethy ,C. S., and Amidan, B., 2004. Survival Estimates for Juvenile Fish Subjected to a Laboratory-Generated Shear Environment. Trans. Am. Fish. Soc. 133, 447–454. https://doi.org/10.1577/02-021

Neitzel, D.A., Richmond, M.C., Dauble, D.D., Mueller, R.P., Moursund, R.A., Abernethy, C.S., Guensch, G.R., 2000. Laboratory studies on the effects of shear on fish: Final report (No. PNNL-13323). Pacific Northwest National Lab. (PNNL), Richland, WA (United States). https://doi.org/10.2172/939056

Ng, E.L., Fredericks, J.P., Quist, M.C., 2015. Effects of Gill-Net Trauma, Barotrauma, and Deep Release on Postrelease Mortality of Lake Trout. J. Fish Wildl. Manag. 6, 265–277. https://doi.org/10.3996/122014-JFWM-096

NOAA, 2024. Developing Methods to Observe Sea Turtle Interactions in the Gulf of Mexico Menhaden Purse Seine Fishery. Exec. Summ. Rep.

O'Keefe, C.E., Cadrin, S.X., Stokesbury, K.D.E., 2014. Evaluating effectiveness of time/area closures, quotas/caps, and fleet communications to reduce fisheries bycatch. ICES J. Mar. Sci. 71, 1286–1297. https://doi.org/10.1093/icesjms/fst063

Pan, Q., Zhang, D., Shi, W., van Esch, B.P.M., 2022. Fish damage assessment during the passage through traditional and fish-friendly axial-flow pumps with Lagrangian tracking approach. Ocean Eng. 253. https://doi.org/10.1016/j.oceaneng.2022.111188

Pan, Y.K., Ern, R., Esbaugh, A.J., 2016. Hypoxia tolerance decreases with body size in red drum Sciaenops ocellatus. J. Fish Biol. 89, 1488–1493. https://doi.org/10.1111/jfb.13035

Pascoe, S., 1997. Bycatch management and the economics of discarding, 370th ed. FAO Fisheries Technical Paper.

Patrick, W.S., Benaka, L.R., 2013. Estimating the economic impacts of bycatch in U.S. commercial fisheries. Mar. Policy 38, 470–475.

Pulver, J.R., Scott-Denton, E., 2012. Observer coverage of the 2011 Gulf of Mexico menhaden fishery. Unpublished.

R Development Core Team, 2014. R: a language and environment for statistical computing.

Raby, G.D., Hinch, S.G., Patterson, D.A., Hills, J.A., Thompson, L.A., Cooke, S.J., 2015. Mechanisms to explain purse seine bycatch mortality of coho salmon. Ecol. Appl. Publ. Ecol. Soc. Am. 25, 1757–1775. https://doi.org/10.1890/14-0798.1

Raoult, V., Williamson, J.E., Smith, T.M., Gaston, T.F., 2019. Effects of on-deck holding conditions and air exposure on post-release behaviours of sharks revealed by a remote operated vehicle. J. Exp. Mar. Biol. Ecol. 511, 10–18. https://doi.org/10.1016/j.jembe.2018.11.003

Rester, J.K., Condrey, R.E., 1999. Characterization and evaluation of bycatch reduction devices in the gulf menhaden fishery. North Am. J. Fish. Manag. 19, 42–50. https://doi.org/10.1577/1548-8675(1999)019<0042:CAEOBR>2.0.CO;2

Rogers, M.W., Barbour, A.B., Wilson, K.L., 2014. Trade-offs in experimental designs for estimating post-release mortality in containment studies. Fish. Res. 151, 130–135. https://doi.org/10.1016/j.fishres.2013.10.020

Sagarese, S.R.N., Scott-Denton, E., Serafy, M.A., Joseph E., 2016. Review of bycatch in the gulf menhaden fishery with implications for the stock assessment of red drum.

Sanderson, S.L., Chesnutt, C.R., Lobel, P.S., 1996. Evidence for ram suspension feeding by the piscivore, Seriola dumerili (Carangidae). Environ. Biol. Fishes 46, 365–373. https://doi.org/10.1007/BF00005014

Schweitzer, C.C., Horodysky, A.Z., Price, A.L., Stevens, B.G., 2020. Impairment indicators for predicting delayed mortality in black sea bass (Centropristis striata) discards within the commercial trap fishery. Conserv. Physiol. 8, coaa068. https://doi.org/10.1093/conphys/coaa068

Smith, W.E., Scharf, F.S., 2011. Postrelease survival of sublegal southern flounder captured in a commercial gill-net fishery. North Am. J. Fish. Manag. 31, 445–454. https://doi.org/10.1080/02755947.2011.590116

Stoner, A.W., 2012. Assessing stress and predicting mortality in economically significant crustaceans. Rev. Fish. Sci. 20, 111–135. https://doi.org/10.1080/10641262.2012.689025

Sulikowski, J.A., Golet, W., Hoffmayer, E.R., Driggers, W.B., Natanson, L.J., Carlson, A., Sweezey, B.B., 2020. Observing post-release mortality for dusky sharks, *Carcharhinus obscurus*, captured in the U.S. pelagic longline fishery. Fish. Res. 221, 105341. https://doi.org/10.1016/j.fishres.2019.105341

Thompson, A.M., Glasgow, J., Buehrens, T., Drucker, E.G., 2011. Mortality in juvenile salmonids passed through an agricultural Hidrostal pump. Fish. Manag. Ecol. 18, 333–338. https://doi.org/10.1111/j.1365-2400.2011.00789.x

Turnpenny, A.W., Davis, M.H., Fleming, J.M., Davies, J.K., 1992. Experimental studies relating to the passage of fish and shrimps through tidal power turbines.

Vaughan, D.S., Shertzer, K.W., Smith, J.W., 2007. Gulf menhaden (Brevoortia patronus) in the U.S. Gulf of Mexico: Fishery characteristics and biological reference points for management. Fish. Res. 83, 263–275. https://doi.org/10.1016/j.fishres.2006.10.002

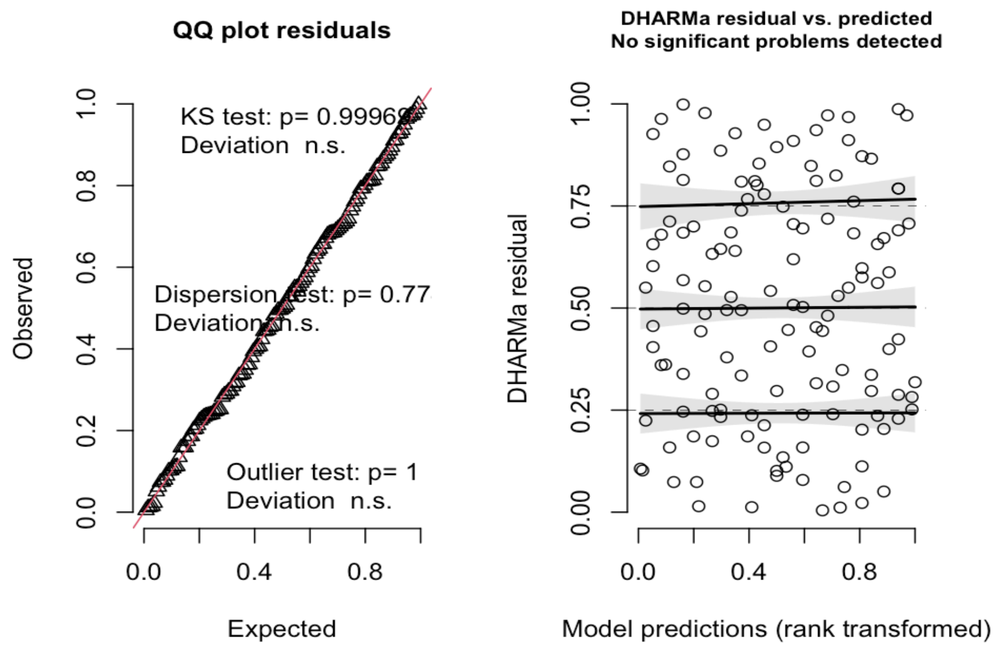
Wegner, N.C., Sepulveda, C.A., Bull, K.B., Graham, J.B., 2010. Gill morphometrics in relation to gas transfer and ram ventilation in high-energy demand teleosts: scombrids and billfishes. J. Morphol. 271, 36–49. https://doi.org/10.1002/jmor.10777

Weltersbach, M.S., Strehlow, H.V., 2013. Dead or alive—estimating post-release mortality of Atlantic cod in the recreational fishery. ICES J. Mar. Sci. 70, 864–872. https://doi.org/10.1093/icesjms/fst038

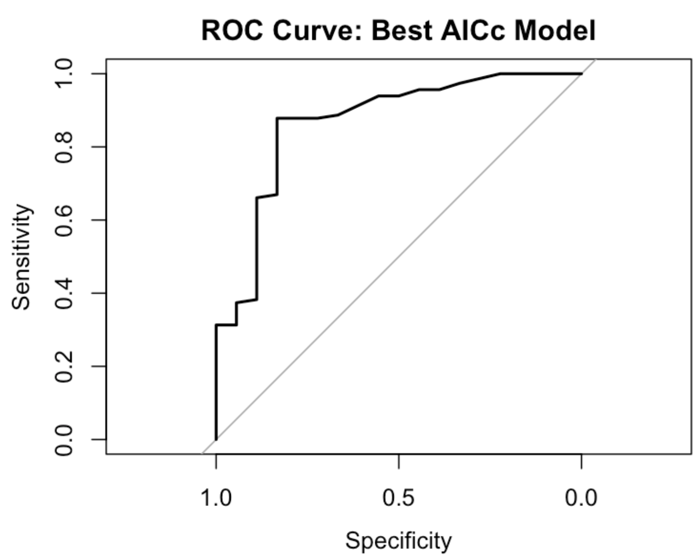
Whitney, N.M., Lear, K.O., Morris, J.J., Hueter, R.E., Carlson, J.K., Marshall, H.M., 2021. Connecting post-release mortality to the physiological stress response of large coastal sharks in a commercial longline fishery. PLOS ONE 16, e0255673. https://doi.org/10.1371/journal.pone.0255673

Yan, Y., Cantoni, E., Field, C., Treble, M., Flemming, J.M., 2022. Spatiotemporal modeling of bycatch data: methods and a practical guide through a case study in a Canadian Arctic fishery. Can. J. Fish. Aquat. Sci. 79, 148–158. https://doi.org/10.1139/cjfas-2020-0267

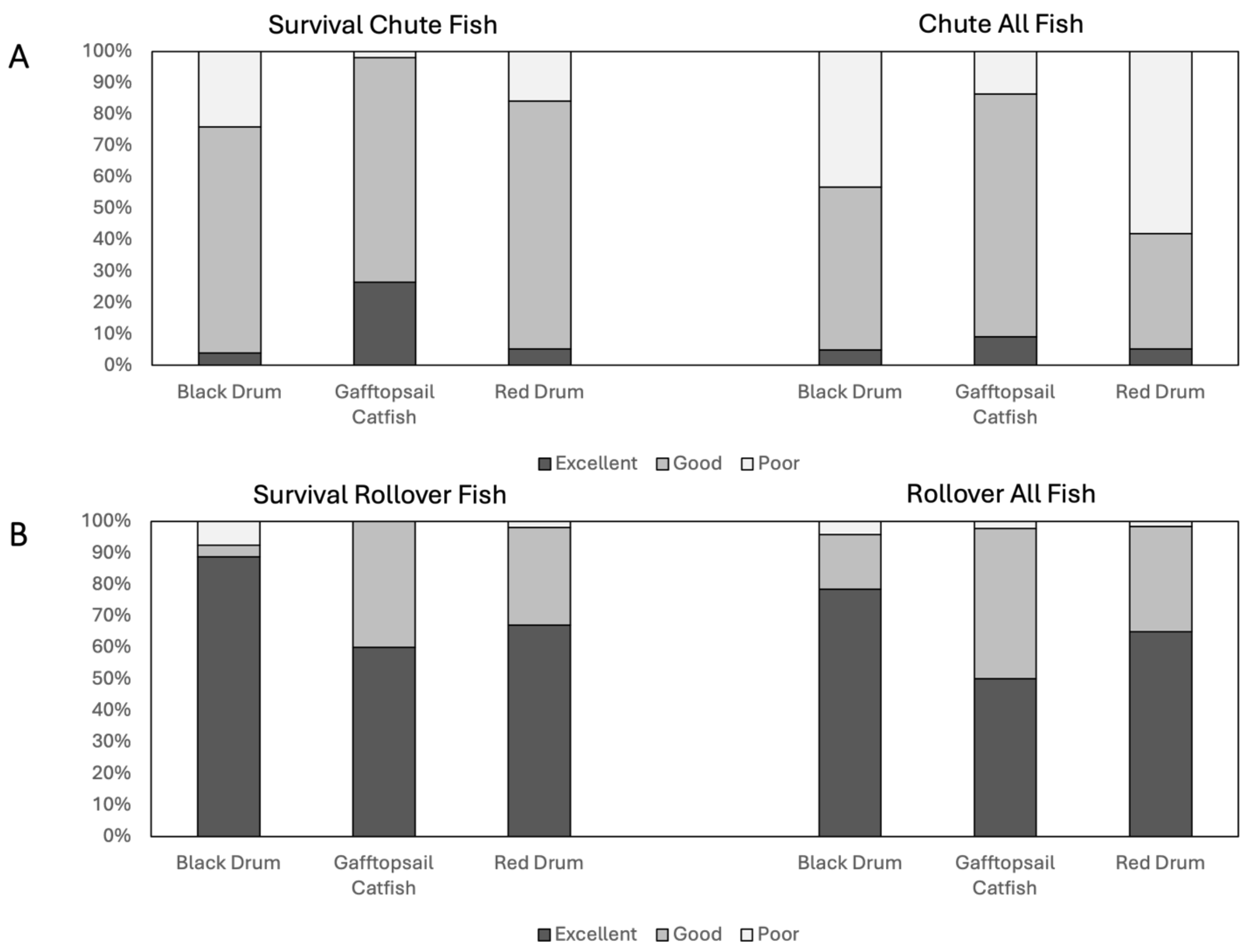
Appendix



Appendix 1. Residual diagnostics for the best-fitting regression model (Survival ~ Dep + Pump + Temp), evaluated using the DHARMa package in R.



Appendix 2. Receiver Operating Characteristic (ROC) curve for the best-fitting logistic regression model. The high area under the curve (AUC) indicates strong discriminatory performance between survival outcomes.



Appendix 3. Proportion of fish with each condition score for A) chute fish tested in the survival study compared all fish sampled in the chute bycatch, and B) rollover fish tested in the survival study compared to the condition scores of all fish sampled in the rollover bycatch. Fish tested in the holding study were thus representative of released bycatch from both the rollover and chute components.