SEDAR21-RD-16

Available online at www.sciencedirect.com

ScienceDirect

Fisheries Research 83 (2007) 238–245

FISHERIES RESEARCH

www.elsevier.com/locate/fishres

The estimated short-term discard mortality of a trawled elasmobranch, the spiny dogfish (*Squalus acanthias*)

John W. Mandelman *, Marianne A. Farrington

Research Department, New England Aquarium, Central Wharf, Boston, MA 02110, USA

Received 4 May 2006; received in revised form 13 September 2006; accepted 1 October 2006

Abstract

To estimate the short-term bycatch discard mortality of otter trawl captured spiny dogfish (*Squalus acanthias*), individuals caught by a Northwest Atlantic commercial bottom-trawl vessel using 45–60 min tows were held in held in pens for 72-h trials in lieu of being released. Mortality rates were compared to those in minimally stressed hook-and-line (control) dogfish subjected to the same protocols. To interpret physiological consequences of trawl capture, blood acid–base parameters were also assessed in dogfish following capture by both trawling and the hook-and-line control. Whole-blood pH (significantly depressed), pCO_2 (significantly elevated) and pO_2 (significantly depressed) were all markedly disturbed in trawled dogfish, indicating that trawl capture elicited a far greater disruption to vascular acid–base balance. However, 72 h mortality was not negligible for control dogfish (24%) but similar to trawling (29%), indicating that pens likely caused the observed (72 h) mortality associated with both capture methods. Still, in evaluating the range of 72 h trawling mortalities found across pen trials, estimated tow-weight was a significant predictor of mortality, explaining 67% of the variation. This suggests that penning stress was merely an additive factor compounding initial capture stress that dictated the 72 h mortality of trawled individuals. When normalized by subtracting out hook-and-line pen mortality, 72 h trawling mortality generally remained well below the 50.0% spiny dogfish discard mortality rate currently estimated for trawling in the Northwest Atlantic and was even superceded by penning stress in lighter tows; a testament to the resiliency of this species. However, catch-weights exceeding 200 kg yielded rapid elevations in 72 h mortality that more closely approached current estimates. This intimates that as tows become more heavily packed, potentially fatal damage inflicted on this species can heighten quickly. Spiny dogfish discard mortality is thus postulated as more commensurate with current estimations for otter trawling when tows are heavily packed.

Keywords: Otter trawling; Bycatch; Discard mortality; Spiny dogfish; *Squalus acanthias*; Capture stress

1. Introduction

The spiny dogfish (*Squalus acanthias*) is a coastal squaloid elasmobranch found in temperate waters worldwide (Compagno, 1984). Like many elasmobranchs, the life history of dogfish is K-selected and characterized by low fecundity, slow growth, a long life span and a close concordance between recruitment and maternal stocks (Nammack et al., 1985; Stevens et al., 2000). Mature female dogfish, whose gestational periods are especially prolonged (18–22 months) (NEFSC, 2003), attain maximally larger sizes then males and are accordingly selected when a directed dogfish fishery exists. Due to these factors, mature female stocks in the Northwest Atlantic were reduced by a reported 75% and (1997–2003) recruitment concomitantly absent as a result of increased dogfish fishing mortality during the 1980s and 1990s (ASMFC, 2002; NEFSC, 2003). The rapidity and magnitude of these declines highlight the difficulty in sustaining Northwest Atlantic dogfish populations during periods of elevated fishing pressure.

Due to the high discard rates of incidentally captured dogfish in the Northwest Atlantic commercial fishing industry, the species' estimated post-release bycatch mortality is of great interest to fisheries management. Such estimates, the need for which were highlighted in the species' Interstate Fishery Management Plan (FMP), are vital in the proper assessment and management of any stock, and can explicate advisable changes in fishing practices and technologies (Chopin et al., 1996; Mesnil, 1996). At present, fishery-models adhere to a 50.0% dogfish bycatch discard mortality rate following otter trawl capture, one of the predominant methods in which dogfish are caught as bycatch in the Northwest Atlantic and in which associated discard mortality estimations have been prioritized

* Corresponding author. Tel.: +1 617 226 2168; fax: +1 617 723 6207.
E-mail address: jmandelman@neaq.org (J.W. Mandelman).

0165-7836/$ – see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.fishres.2006.10.001

by management (NEFSC, 2003). However, initial studies have reported lower post-capture/discard mortality rates for trawled dogfish (Mandelman and Farrington, 2007); John Chisholm, personal communication). Consequently, the present study sought to expand the estimations of mortality for this group of discards by monitoring trawled dogfish in pens for 72 h in substitution for a return to the ocean. These rates of discard mortality were then compared to those following 72 h pen containment in dogfish captured by rapid hook-and-line, a method that is more abbreviated than trawl capture and was presumed to be comparatively less intensive.

The analysis of spiny dogfish blood physiology, which has previously been utilized to assess the physiological status of captured elasmobranchs (e.g. Cliff and Thurman, 1984; Wells and Davie, 1985; Manire et al., 2001), was concurrently evaluated in dogfish to help ascertain the effects of trawl capture. Whole-blood pH has been shown to correlate most extensively with additional secondary blood parameters in juvenile dusky sharks (*Carcharhinus obscurus*) (Cliff and Thurman, 1984) and in the spiny dogfish (personal observation). Consequently, this parameter and, the partial pressures of whole-blood gases were assessed as indicators of physiological status following trawling in the present study. In an attempt to establish minimally stressed blood levels and to establish whether trawling elicited physiological disturbances in this species, a subset of control dogfish, again caught rapidly by hook-and-line, were subjected to identical blood sampling and analytical protocols.

2. Methods

All fieldwork was conducted aboard Fishing Vessel *Joanne A III* (Chatham, MA, USA) southeast of Chatham Lighthouse and additional areas southeast of Chatham Inlet (Fig. 1). To ensure adequate spiny dogfish catch biomass, trips were run in the summer months between June and September (2004) when the species is typically most abundant in the experimental area and thereby incidentally captured at high rates during normal fishing operations. Trawling (in depths ranging 66.0–73.0 m) and hook-and-line fishing (in depths ranging 46.0–56.0 m) were conducted on cobble and sand bottom, with diversities in bottom-seawater (6–11 °C), surface-seawater (13–16 °C), and air (20–29 °C) temperatures. Depths and locations were recorded for every fishing set and pen trial.

2.1. Specimens captured by trawl

Efforts were made to adhere to standard fishing practices aboard the vessel. The size and capacity of the vessel as well as

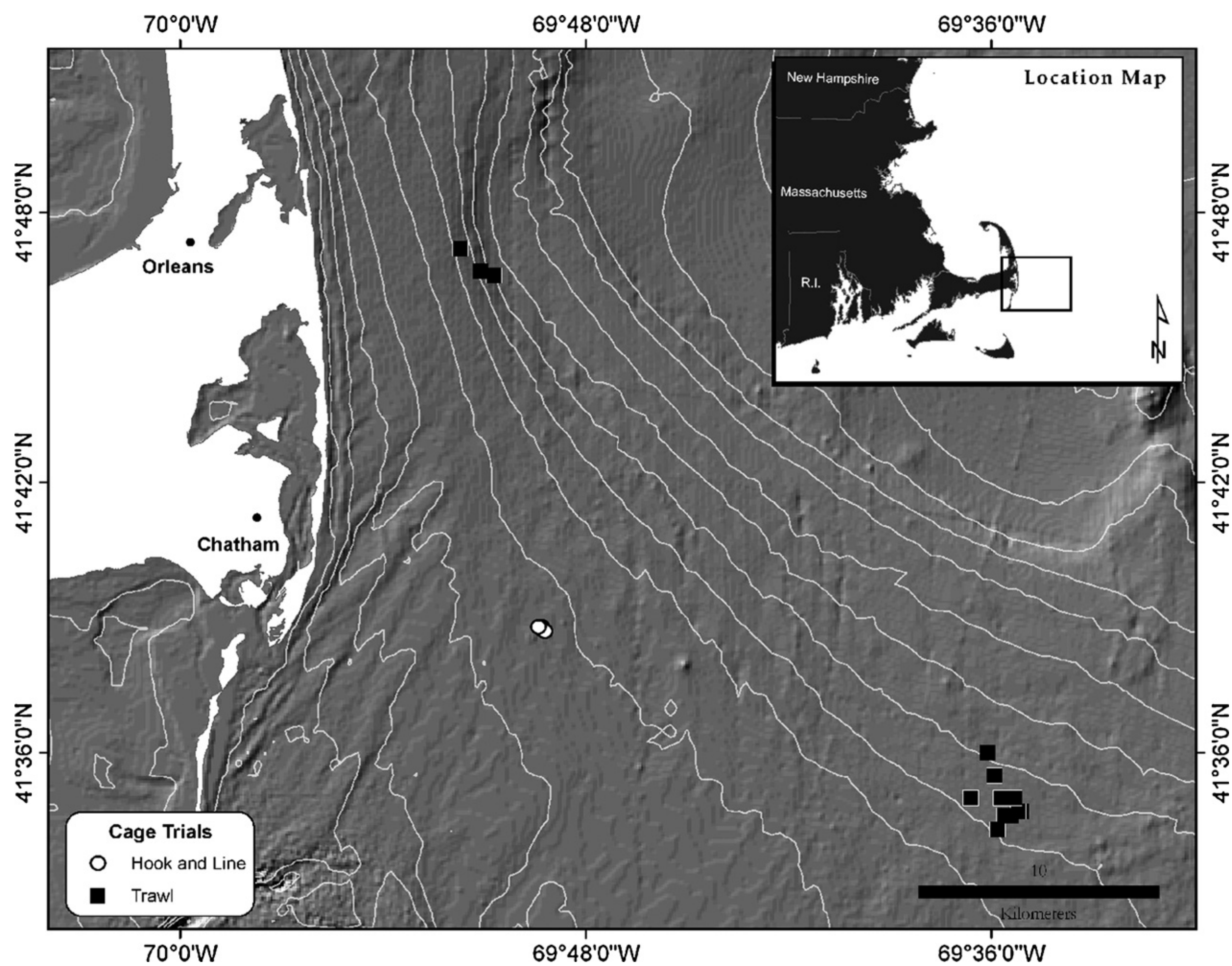

Fig. 1. Map of the experimental region (trawling and hook-and-line capture, physiology and mortality investigation). The clustering of 72 h pen trials was not a function of the experimental design and had no impact on mortality.

the catch potential of the trawl gear, which will be described as follows, fell into what was presumed to be the median range for members of the Northwest Atlantic bottom trawl fleet (anonymous industry source, personal communication). Trawling was conducted using a 350 hp semi-high-rise Danish otter trawl with 302 meshes in the fishing circle. The mesh-size was 15.2 cm and twine diameter of 3.0 mm (16.5 cm^2 in the codend). The net possessed 15 fathom top and bottom legs and 20 fathoms of ground-cable. Trawl doors weighed 454 kg. A hard-bottom sweep on the bosom section was implemented to avoid boulders on the substrate. A total of 26 hauls ranging in estimated catch-weights between 90.0 and 400.0 kg were conducted in order to fulfill an adequate number of pen trials. As fishermen were instructed to abide by normal routines for their vessel during this particular period, duration-of-tow varied between 45 and 60 min with a mean (±S.E.M.) of 46.31 (5.79) min. As spiny dogfish tend to congregate by size and upon reaching adulthood, by gender (ASMFC, 2002), many catches were disproportionately segregated according to these factors.

In order to account for the deck-time that typically occurs while the catch is sorted on this vessel, the treatment (handling) of trawled dogfish persisted for at most 20.0 min following haul-back. During this period, dogfish were arbitrarily assigned to one of the following two treatments: (1) evaluated for gender and total length (TL) (tip of snout to extended tip of hypochordal caudal lobe) and subjected to phlebotomy in order to gauge whole-blood pH values following trawl capture; or (2) housed in sea pens (72 h) to monitor discard mortality. To avoid exacerbating the stress induced by capture, itself, penned dogfish were not tagged. Thus, gender and size of these individuals were recorded upon completion of the 72 h trials.

2.2. Specimens captured by hook-and-line

Each short set consisted of five squid-baited standard circle hooks hung in the water-column (not directly on the substrate) from a short makeshift longline. Due to opportunistic feeding displayed by dogfish and general ease of capture, this method enabled the landing of individuals within 3 min of hook deployment. Each set was rapidly retrieved by hand and dogfish were immediately de-hooked and either (1) sexed, measured, blood sampled and released; or (2) placed in the temporary holding bins (1.85 m × 1.0 m and 1.0 m deep with a ∼1000.01 seawater capacity) if awaiting subsequent pen-deployment. The holding mechanisms were flushed with ambient seawater and dogfish were never held for more than 10 min prior to being deployed in the pens. Although each animal experienced laceration from being hooked, bleeding subsided rapidly as evidenced by the lack of blood in the seawater holding tanks after roughly 1 min. As with trawled dogfish, tagging did not occur and sexing and measuring ensued after the 72 h trials for hook-and-lined dogfish monitored for mortality in pens. Female dogfish were absent during this phase of the study precluding the analyses of gender as a potential variable affecting 72 h mortality.

2.3. Post-capture phlebotomy

Approximately 1.0 ml blood samples were obtained by caudal-veni puncture using non-heparinized 20 gauge (0.04 m) stainless steel syringe needles fitted to 5 ml plastic syringes (Becton, Dickinson and Company, Franklin Lakes, NJ). This is a rapid and relatively non-invasive method of blood collection in elasmobranchs that limits the disturbance of the animal (Cooper and Morris, 1998). Upon obtaining a sample, needles were immediately plugged with cork (to slow diffusive gas loss) and 20.0 μl deposited into individual (CG4+) cartridges for duplicate assays in i-STAT portable clinical analyzers (Heska Corporation, Fort Collins, CO) within 10 s of being drawn. The whole blood from a of total of 29 and 13 dogfish was analyzed for pH and the partial pressures of carbon dioxide (pCO_2) and oxygen (pO_2) following trawl and post-hook-and-line capture, respectively. As the study only sought to reflect relative differences as a function of capture method, pH and blood gas readings were derived using clinical analyzers temperature-calibrated for the blood of mammals as opposed to ectotherms. Thus, a cautious approach should be taken if interpreting these data as absolute values.

2.4. Pen design and construction

Holding pens were comprised of a PVC skeleton encircled by a contoured netting design. To prevent sensory overload for the spiny dogfish, metal was completely excluded from the design. Each of the eight rectangular pens measured 3.7 m × 1.2 m × 1.2 m and was book-ended by two 1.2 m × 1.2 m sections (Fig. 2). A 1.2 m × 1.2 m permanently fixed middle section and eight removable 1.8 m PVC sections enabled pen-compression and easier storage and transport. This enabled on-deck expansion while tows were in progress. Pens were custom-made with 25.0 mm mesh-sized netting tailored to encase the frame (Nylon Net Company, Memphis, TN). To simplify placement and removal of dogfish while reducing escape potential during deployment, the 72 h trials and retrieval of pens, the netting for each pen was equipped with a specialized Velcro-bound aperture. The frames were constructed with 25.0 mm

Fig. 2. Photograph (unmodified but reduced to scale) of an experimental pen just after construction. Measurements are 3.7 m × 1.2 m × 1.2 m.

schedule-40 PVC with holes drilled along the lengths of each section and joint to ensure negative buoyancy. The pens were maneuvered in the water column using bridles secured to whale-safe swivels connected to a primary tag-line.

2.5. Experimental pen work (72 h mortality)

To secure that characteristics of a trawl (e.g. estimated catch-weight) could subsequently be correlated to 72 h mortality rates, a particular experimental pen was only deployed with dogfish from a single tow. In order to maximize sample sizes and minimize crowding, the targeted dogfish quota was set at 16 animals per pen (relative to both capture methods). Once that number was obtained, each pen was hydraulically maneuvered along the vessel's stern, released to the freely descend to the seafloor, and anchored to the substrate with either a 36.3 kg railroad tie or an 18.1 kg mushroom anchor. Left *in situ*, each pen was retrieved after 72 h. In addition to being mapped for location, pens were marked with a surface buoy and highflyer with radar reflector. Pens were situated at a mean (±S.E.M.) depth strata of 60.0 (0.9) m and because these levels did not vary significantly between trials, stratum was not analyzed as a study variable.

A total of 185 trawled dogfish (106 females, 79 males), ranging in length between 61 and 93 cm, was held across 11 pen trials to assess discard mortality. Individuals varied in size between 61.0 and 93.0 cm. A total of 55 hook-and-lined dogfish (all male), ranging in length between 70 and 85 cm, was monitored across four pen trials.

2.6. Statistical analyses

χ^2 analysis was used to assess differences in mortality between pen trials (both capture methods), capture-methods and sexes (trawl only). Independent samples *t*-tests were utilized to compare mean-live versus mean-dead animal size within each gender (trawl) and males only (hook-and-line). To test whether reproductive maturity affected trawl mortality, a χ^2 analysis was used to assess differences in mortality between females below or exceeding 80.0 cm. In order to correlate aspects of a particular trawl with resulting rate of 72 h mortality, a forward stepwise regression was utilized to assess how estimated tow-weight, tow-duration, gender composition (percent female in a pen trial), dogfish-size and coefficient of variation of size (variance × mean^{-1}) determined percent-mortality of dogfish within a specific pen. Variables were added if $F > 4.00$. To assess whether pen containment was the primary causative factor in dogfish mortality or an additive stressor compounding capture stress, mean pen mortality in trawl trials was normalized by subtracting the mean control mortality (hook and line trials). The trawling mortality was considered significantly greater than the control if the 95% confidence interval from the normalized trawl mortality exceeded zero. Significant covariates of mortality (step-wise analysis) were then compared to normalized trawl mortalities to determine whether that factor could predict mortality rates after adjusting for the effect of pen containment. A linear regression was also utilized to determine whether the duration of a trawl could predict for the estimated weight of its catch.

Analysis of variance (ANOVA) was utilized to assess potential differences in mean blood parameters between tows (trawl capture only). In cases where differences in mortality between trials or between mean physiological values across multiple tows in dogfish were not significant, data were pooled subsequent to further analyses. Differences in mean blood parameter values between capture methods, while adjusting for the total length (covariate) of dogfish, were assessed by one-way analyses of covariance (ANCOVAs). In cases of Heteroskedastic variances or non-normal distributions related to the blood parameters, Welch ANOVA tests were utilized and/or a conservative interpretation of the data (results were reported as significant according to $\alpha = 0.001$) was employed. Otherwise, results were reported as significant according to $\alpha = 0.05$. All analyses were performed using JMP 4.04 Software (SAS Institute, Cary, NC).

3. Results

3.1. Experimental pen mortality

There was no immediate post-capture trawl mortality. As no significant differences in mortality were found between the 11 pen trials ($\chi^2_{10} = 8.82$, $P > 0.5$), discard mortality data across pens was pooled for the purposes of comparing overall 72 h mortality versus hook-and-line. Trawled dogfish exhibited a 29% 72 h mortality rate in pens. There was no effect of dogfish total length (TL) on trawl 72 h discard mortality as demonstrated by the similarity in this factor between live and dead dogfish within both male (independent samples *t*-test: $t_{75} = 0.35$, $P > 0.7$) and female (independent samples *t*-test: $t_{100} = 0.73$, $P > 0.4$) dogfish samples. Females exceeding 80 cm displayed similar mortality rates to those below that threshold ($\chi^2_1 = 0.13$, $P > 0.7$).

Of the factors that could potentially correlate to 72 h mortality (tow-weight, tow-duration, gender composition, dogfish-size and coefficient of variation of size), only estimated tow-weight was significantly correlated with mortality (one-way ANOVA: $F_{1,9} = 7.35$, $P = 0.024$). This factor explained 67% of the variation in 72 h mortality (Fig. 3A). The remaining factors failed to enter the model ($F < 0.2$ for each). The duration of a trawl was not a significant predictor of its estimated catch-weight ($R^2 = 0.16$, $P > 0.2$).

3.2. Hook-and-line (control) pen mortality

There was no immediate post-capture hook-and-line mortality. As no significant differences in 72 h mortality were found between the four pen trials ($\chi^2_3 = 2.07$, $P > 0.5$), these data were pooled for the purposes of comparing overall 72 h mortality versus trawling. The collective 72 h mortality rate (±standard deviation) for hook-and-line captured dogfish (24 ± 6%) was similar to that found for otter trawled dogfish (29% = ±12%) (χ^2, $P > 0.1$). Mean (±S.E.M.) total body-length of live males (76.7 ± 0.4 cm) was significantly exceeded

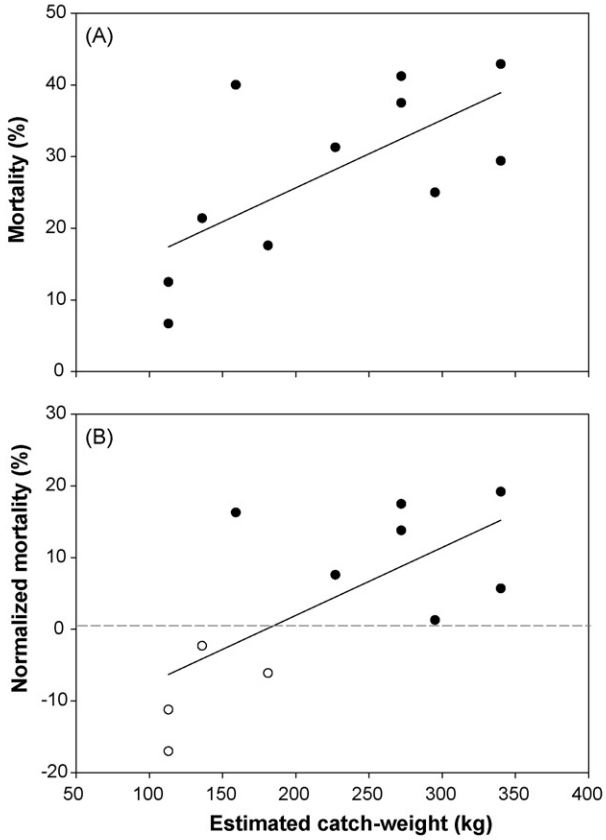

Fig. 3. Estimated catch-weight as a predictor of (A) 72 h post-trawl mortality in associated pen trials following trawl capture. Forward stepwise regression $(R) = (67\%)$; $(R^2) = 0.45$. See text for additional stepwise regression data and; (B) normalized 72 h post-trawl mortality in associated pen trials (calculated as trawling mortality/pen trial − mean hook-and-line mortality) ($R^2 = 0.45$, $P < 0.03$). Solid ovals represent positive adjusted (pen trial) mortality values while hollow ovals denote pen trials where mean hook-and-line mortality exceeded trawl mortality.

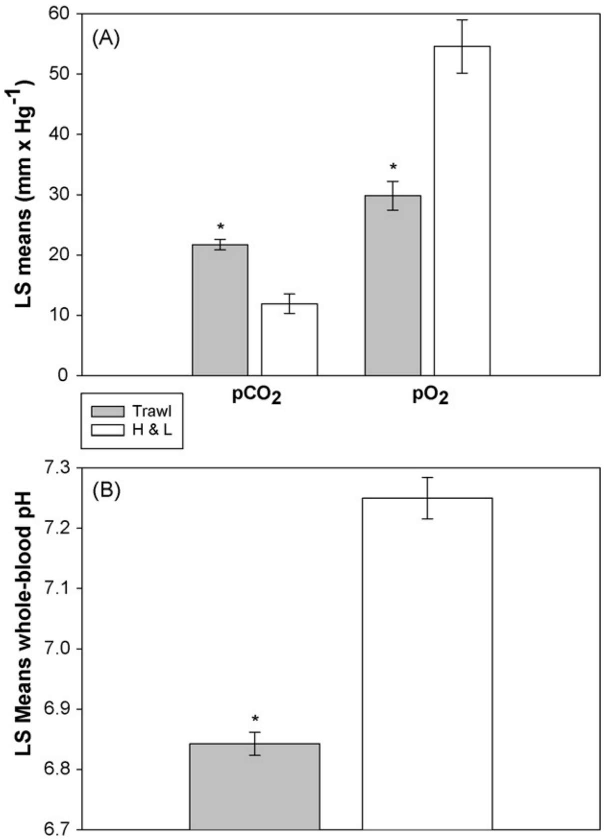

Fig. 4. The effects of trawl vs. hook-and-line capture on whole-blood acid–base parameters from a subset of spiny dogfish (*Squalus acanthias*). Least squares means (±S.E.M.) whole blood: (A) pCO_2 and pO_2; (B) pH, for trawl and hook-and-line caught dogfish when accounting for dogfish-size (covariate). Asterisks denote significant ($P \leq 0.001$) differences with hook-and-line caught dogfish in relation to a specific blood parameter. Post-trawl ($n = 29$); post-hook-and-line ($n = 13$).

that of dead males (73.9 ± 0.7 cm) (independent samples t-test: $t_{50} = 3.15$, $P < 0.003$) implying a potential size-effect on mortality.

When normalized by subtracting the mean hook-and-line pen mortality rate (24%) from mortality rates observed after 72 h trawling pen trials, four trial values fell below zero (Fig. 3B). Thus, the 95% confidence interval from the normalized trawl mortality estimates failed to exceed zero implying that trawl mortality was not solely induced by pen containment. However, the four trials with negative values possessed estimated catch weights less than 200 kg. Estimated catch-weight therefore remained a positive predictor of trawl discard mortality after normalization for pen effects in more packed (>200 kg) tows ($R^2 = 0.45$, $P < 0.03$) (Fig. 3B). Thus, in lighter tows, pen-effects caused fatalities whereas in tows exceeding 200 kg, 72 h mortality resulted from the additive impact of trawling stress and pen containment.

3.3. Post-capture phlebotomy

Because inter-tow variations in mean whole-blood pH, pCO_2 and pO_2 were not significant (one-way analyses of variance (ANOVA): $F_{8,28}$, $P > 0.5$ in each case), post-trawl values from the multiple tows were pooled for analyses. When accounting for the size of dogfish (covariate), one-way ANCOVA results revealed a significant effect for the treatment factor capture-method when evaluating whole-blood pH ($F_{1,38} = 106.04$, $P < 0.0001$); whole-blood pCO_2 ($F_{1,38} = 24.9$, $P < 0.0001$); and whole-blood pO_2 ($F_{1,38} = 17.17$, $P = 0.0002$). Least squares adjusted whole-blood pO_2 (Fig. 4A) and pH (Fig. 4B) means were significantly more depressed in trawled dogfish than in hook-and-line caught dogfish, while least squares adjusted whole-blood pCO_2 means were significantly more elevated in trawled dogfish than in hook-and-lined dogfish (Fig. 4A).

4. Discussion

4.1. Mortality and potential pen influences

In general, the post-release mortality of spiny dogfish in the present study (29%) is similar to the 25% found previously in trawled dogfish (John Chisholm, personal communication); both figures lower than the 50% currently estimated in the fishery (NEFSC, 2003). Before comparing these figures to the estimated discard mortality rate currently upheld by management however, the mortality resulting from by the capture/handling/deck-time itself must be distinguished from that caused by extraneous factors and the variability in mortality found across pen trials must be addressed.

First, it is critical to account for the potential contribution of the pens on the observed fatalities. The strongest causative indicator of such lies in the moderate mortality rates found in hook-and-lined (24%) dogfish, despite exposure to what was presumed to be only minimal stress. These control dogfish were subjected to rapid fight times and negligible air-exposure, displayed comparatively extreme vigor upon capture, and exhibited blood acid–base values, to be addressed shortly, that mirror presumed near-basal levels for the species (Mandelman and Farrington, 2007). Based upon these attributes, it is not believed that hook-and-line capture exclusively would have been lethal. The assumption that penning stress induced mortality in hook-and-lined dogfish intimates that similar effects were imposed on trawled dogfish, who were exposed to analogous pen conditions. Negligible mortality (two fatalities in 34 total animals) has previously been found in dogfish caught across multiple tows commensurate to those in the present study. Unlike being held in pens, however, those individuals underwent sea and land transport and 30 subsequent days in captivity; treatments presumed to have induced stress beyond the trawl capture alone (Mandelman and Farrington, 2007). These factors suggest that penning, as has been postulated in previous studies addressing discard mortality in teleosts (e.g. Milliken et al., 1999), was quite stressful in the current study, acting upon dogfish caught by both trawling and hooking. Although the direct effects that caused mortality in pens are uncertain, potential detriments from this type of containment on dogfish are thought to have included confinement stress on physiology, physical interactions with the pen's infrastructure and netting (e.g. physical trauma or immobilization due to becoming entrapped), and/or foraging by scavenging sea lice (order isopoda) in the cases when individual dogfish became moribund in pens.

As pens are presumed to have influenced mortality, it would be expected that any potential effects on mortality caused by characteristics of the tows themselves would have been obscured and difficult to distinguish, especially in cases where tow effects were only marginally significant. The confounding stress from towing and penning likely explains why larger overall body-size failed to enhance discard survival in trawled dogfish as was seen in hook-and-lined dogfish herein and previously in trawled teleosts (e.g. Davis and Olla, 2002; Sangster et al., 1996; Suuronen et al., 1996). However, estimated catch-weight was found to be a significant predictor of inter-pen mortality; an effect that remained discernable even after normalizing trawling mortality for perceived pen effects by subtracting out the average hook-and-line (control) mortality. This suggests that the artifact of the tow experience, one which dictates the degree of compaction with the gear and accompanying catch biomass, had a strong influence on the mortality of trawled dogfish. Penning appears to have been a additive stressor acting upon trawled dogfish captured by the heavier tows (e.g. those exceeding 200 kg) while the primary stressor inducing mortality in lighter tows and in hook-and-lined dogfish. As tow duration was held relatively constant here, catch-weight, which is not a factor that can be manipulated, independently had bearing on mortality in this species. Intuitively, the catch is subjected to increasing strain the longer a packed tow is dragged. However, as duration was not a positive predictor of tow-weight, longer tows do not necessarily equate to greater catch weights and consequential packing stress. The results of this study imply that in relation to the vessel and gear employed, tows not necessarily be especially prolonged to incite moderate levels of mortality in this species.

4.2. Blood acid–base balance

Relative to values from hook-and-lined individuals, whole-blood pH and gas partial pressures in trawled dogfish were significantly disturbed in the present study. Anoxia and exhaustion from sustained swimming and net entrapment respectively are among the many stressors that have been linked to capture by towed gear in fishes (Davis, 2002). These factors, which induce lactic acidosis and hypercapnia, drive concomitant decreases in extracellular pH through metabolic ([H^+] elevation and [HCO_3^-] depression) and respiratory ($p$$CO_2$ elevation) acidosis (Heisler, 1988).

Despite the likelihood that the specific moment of dogfish capture varied between individuals and tows and that ultimate mortality varied partly as a function of variable catch-weights, post-capture blood gas and pH values were similarly perturbed in dogfish across the varied hauls in the present study. This suggests that these parameters became altered relatively rapidly, but since mortality at the time of capture was nonexistent, changes were not outright lethal in scope. While immediately discernable drops in blood pH have been reported in exhaustively exercised (Piiper et al., 1972) and confined (Cliff and Thurman, 1984) elasmobranchs of comparable stature to spiny dogfish, the magnitude of blood pH declines found presently in trawled dogfish was greater than that in the other studies, indicating that trawling stress was especially acute in this species. However, dogfish have demonstrated the capacity to survive even after exhibiting blood alterations of similar magnitude (Mandelman and Farrington, 2007). This and the high number of surviving trawl-caught dogfish in the present study intimate that the species is capable of withstanding and resolving large-scale disturbances to extracellular acid–base balance. In fishes, potentially lethal shifts in intracellular pH are avoided at the expense of more extreme changes in extracellular levels (Milligan and Wood, 1986). Conversely, hook-and-lined dogfish with minimally stressed post-capture blood acid–base values displayed comparable 72 h mortality rates as trawled dogfish. Thus, although the assessment of blood physiology can provide considerable insight regarding the stress response due to capture, disruptions or lack thereof do not necessarily portend mortality.

4.3. Prolonged fate of trawled dogfish and conclusions

When adjusting for presumed pen effects, the range of spiny dogfish 72 h (discard) mortality in the present study was well below the 50% presently estimated following discard of the species in the actual bottom-trawl fishery. However, in relation to the fishing gear and operations employed herein, discard mortality may increase rapidly as catch weights rise in excess of 200 kg. Although this study and others have demonstrated the species to possess a high threshold for the stressors linked to trawling, the discard mortality of dogfish caught in more heavily packed tows is presumed to more closely resemble the estimate upheld in current dogfish stock assessments. Since a tow's duration unlike its weight is controllable, methods to promote survivability might be to abort tows in instances when possible to avoid large nearby aggregations or if able to perceive a large dogfish catch in-tow. As biomass capacity is proportional to the size of trawling gear, the impacts of catch weight could be even greater in vessels/gear exceeding those utilized in the present study and is thus an important factor to consider.

Although the 72 h monitoring window likely accounted for short-term fatalities, the fate of dogfish beyond 72 h remains uncertain and merits investigation. Delayed cryptic effects, which have been shown to increase discard mortality rates (Davis, 2002), include greater vulnerability to predation (Davis and Olla, 2001), delayed infection (Neilson et al., 1989) and immunosuppression (Lupes et al., 2006).

Additional work related to discard mortality rates in trawled dogfish should address the effects of wide discrepancies in tow duration (commercial tows may be more abbreviated or prolonged relative to those investigated in the present study), deck-times, seasonality and the age of dogfish (e.g. juvenile escapees versus adult discards). As trends not germane to this manuscript have alluded to potential sex-specific mortality and responses to stress in dogfish, additional investigation addressing this factor (in dogfish and other elasmobranchs) as a variable potentially impacting the stress response and mortality associated with commercial fishing capture is recommended.

For studies seeking to assess mortality through the use of holding pens at sea, the implementation of camera systems is highly encouraged to better document pen-effects. As adult dogfish have demonstrated the ability to quickly acclimate to round seawater holding tanks (Mandelman and Farrington, 2007), the utilization of round as opposed to more narrow rectangular pens, which allow more breadth as opposed to sheer volume, is predicted to be a less stressful method for investigating discard mortality in motile species at sea.

Acknowledgements

The authors would like to thank Captain's Bill and Jason Amuru for their expertise and assistance during fishing operations and pen deployment/retrieval processes, John Chisholm for providing essential consult regarding the pen construction and experimental protocols, and Northeastern University's Marine Science Center (Nahant, MA) for the invaluable usage of space to both construct and store pens. Extensive assistance in the field was provided by several New England Aquarium staff/volunteers, most prominently Tom Fisher and Deana Edmunds. We would also like to thank B. Scott Nunez, Sal Genovese and Michael Tlusty for providing critical feedback regarding this manuscript. This work comprised a portion of JWM's doctoral research (Northeastern University, Boston, MA) and was funded by the Northeast Region of the National Marine Fisheries Service through a Saltonstall–Kennedy Grant to MAF and JWM, as well as the New England Aquarium's Research Department.

References

Atlantic States Marine Fisheries Commission (ASMFC), 2002. Interstate Fishery Management Plan for Spiny Dogfish. Fishery Management Report No. 40, Washington, DC.

Chopin, F.S., Arimoto, T., Inoue, Y., 1996. A comparison of the stress response and mortality of sea bream Pagrus major captured by hook and line and trammel net. Fish. Res. 28, 287–289.

Cliff, G., Thurman, G.D., 1984. Pathological and physiological effects of stress during capture and transport in the juvenile dusky shark Carcharhinus obscurus. Comp. Biochem. Physiol. A 78, 167–173.

Compagno, L.V.J., 1984. Hexanchiformes to lamniformes. Sharks of the world. An annotated and illustrated catalogue of shark species known to date. FAO Fish. Synop. 125, 1–249.

Cooper, A.R., Morris, S., 1998. The blood respiratory, haematological acid–base and ionic status of the port jackson shark, Heterodontus portusjacksoni, during recovery from anaesthesia and surgery: a comparison with sampling by direct caudal puncture. Comp. Biochem. Physiol. A 119, 895–903.

Davis, M.W., 2002. Key principles for understanding fish bycatch discard mortality. Can. J. Fish. Aquat. Sci. 59, 1834–1843.

Davis, M.W., Olla, B.L., 2001. Stress and delayed mortality induced in Pacific halibut Hippoglossus stenolepis by exposure to hooking, net towing, elevated sea water temperature and air: implications for management of bycatch. N. Am. J. Fish. Manage. 21, 725–732.

Davis, M.W., Olla, B.L., 2002. Mortality of lingcod towed in a net is related to fish length, seawater temperature and air exposure: a laboratory bycatch study. N. Am. J. Fish Manage. 22, 395–404.

Heisler, N., 1988. Acid–base regulation. In: Shuttleworth, T.J. (Ed.), Physiology of Elasmobranch Fishes. Springer, Berlin, pp. 215–252.

Lupes, S.C., Davis, M.W., Olla, B.L., Schreck, C.B., 2006. Capture-related stressors impair immune system function in sablefish. Trans. Am. Fish. Soc. 135, 129–138.

Mandelman, J.M., Farrington, M.A., 2007. The physiological status and mortality associated with otter trawl capture, transport, and captivity of an exploited elasmobranch *Squalus acanthias*. ICES J. Mar. Sci. 64.

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.

Mesnil, B., 1996. When discards survive: accounting for survival of discards in fisheries assessments. Aquat. Living Resour. 9, 209–215.

Milligan, C.L., Wood, C.M., 1986. Intracellular and extracellular acid–base status and H^+ exchange with the environment after exhaustive exercise in the rainbow trout. J. Exp. Biol. 123, 93–121.

Milliken, H.O., Farrington, M.A., Carr, H.A., Lent, E., 1999. Survival of Atlantic cod (*Gadus morhua*) in the Northwest Atlantic longline fishery. Mar. Technol. Soc. J. 33, 19–24.

Nammack, M.F., Musick, J.A., Colvocoresses, J.A., 1985. Life history of spiny dogfish off the Northeastern United States. Trans. Am. Fish. Soc. 114, 367–376.

Neilson, J.D., Waiwood, K.G., Smith, S.J., 1989. Survival of Atlantic halibut (*Hippoglossus hippoglossus*) caught by longline and otter trawl gear. Can. J. Fish. Aquat. Sci. 46, 887–897.

Northeast Fisheries Science Center (NEFSC), 2003. 37th Northeast Regional Stock Assessment Workshop (37th SAW) Advisory Report. Northeast Fisheries Science Center Reference Document 03-17, pp. 19–30.

Piiper, J., Meyer, M., Drees, F., 1972. Hydrogen ion balance in the elasmobranch, Scyliorhinus stellaris, after exhausting activity. Resp. Physiol. 16, 290–303.

Sangster, G.I., Lehmann, K., Breen, M., 1996. Commercial fishing experiments to assess the survival of haddock and whiting after escape from four sizes of diamond mesh cod-ends. Fish. Res. 25, 323–345.

Stevens, J.D., Bonfil, R., Dulvy, N.K., Walker, P.A., 2000. The effects of fishing on sharks, rays, and chimaeras (chondrichthyans) and the implications for marine ecosystems. ICES J. Mar. Sci. 57, 476–494.

Suuronen, P., Erickson, D.L., Orrensalo, A., 1996. Mortality of herring escaping from pelagic trawl codends. Fish. Res. 25, 305–321.

Wells, R.G.M., Davie, P.S., 1985. Oxygen binding by the blood and hematological effects of capture stress in two big game-fish: mako shark and striped marlin. Comp. Biochem. Physiol. A 81, 643–646.