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Recreational fishing fight times are not correlated with physiological status of blue sharks (*Prionace glauca*) in the Northwestern Atlantic

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ABSTRACT

Sharks, like other fish, react to capture and handling stress with more exaggerated physiological responses than most other vertebrates, and the potential consequences of their capture include both sub-lethal and lethal effects. Blue sharks, *Prionace glauca*, are one of the most heavily exploited species of sharks in the world, both in commercial and recreational fisheries, and while the capture response of blue sharks in commercial fisheries has been comparably well-studied, there is a relative lack of information regarding the influence of handling and capture on the species in the recreational setting. Our analysis of blood-based biomarkers, such as glucose, lactate, pH, and plasma electrolytes, sampled from twenty blue sharks captured in the recreational fishery suggests that over the short hook times (time on the line) characteristic of the fishery, blue sharks do not fight to the point of blood acidosis and are likely able to withstand capture and handling in a catch-and-release setting. We did note an inverse relationship between shark total length and blood glucose levels, suggesting the possibility that smaller individuals may be more susceptible to capture stress, but this variation may also reflect other metabolic factors or an ontogenetic shift in diet. We discuss these findings within the context of the recreational fishery, including priorities for angler education.

1. Introduction

Fish react to capture and handling stress with more exaggerated physiological responses than most other vertebrates (Barton, 2002; Marshall et al., 2012; Skomal, 2006). In particular, capture can induce physiological and homeostatic disturbances resulting in anaerobic states, changes in blood physiology (e.g., accumulation of metabolites), and exhaustion (reviewed in Davis, 2002). Depending on the magnitude of these changes, the consequences can range from sub-lethal effects, such as changes in behavior, health, condition, and fitness, to lethal effects which can have population level impacts (Cooke et al., 2002; Davis, 2002; Wilson et al., 2014). The population implications of these effects are important to consider for threatened marine species such as sharks, which have been experiencing population declines due to commercial and recreational fishing mortality at a global scale (e.g., Pacoureau et al., 2021; Worm et al., 2013).

Investigations into the physiological and behavioral impacts of fisheries interactions on sharks are increasing in frequency, and over time have increased our body of knowledge on a species, region, and fisheries-specific basis (Dapp et al., 2017; Gallagher et al., 2014a; Guida et al., 2016; Jerome et al., 2018). Capture stress in sharks has most commonly been measured through blood-based biomarkers such as pH, glucose, lactate, and plasma electrolytes (e.g., K+, Ca^{2+}, PO_4^{3}) (Cliff and Thurman, 1984; Gallagher et al., 2014a; Mandelman and Skomal, 2009; Skomal, 2006; Wedemeyer and Yasutake, 1977;Wells et al., 1986). Whereas the majority of shark species assessed have been those commonly encountered in longline bycatch (e.g., Butcher et al., 2015; Gallagher et al., 2014b), in recent years there has been a focus on

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triaging species of emerging conservation concern including assessments of IUCN Red List Threatened species (e.g., smalltooth sawfish, *Pristis pectinata*; Prohaska et al., 2018), as well as CITES-listed species (e.g., white shark, *Carcharodon carcharias*; Gallagher et al., 2019). However, there is still a need to sample species that are at the greatest risk of overexploitation due to their wide-ranging distribution and overlap with fisheries-related stressors.

Blue sharks, *Prionace glauca*, are one of the most heavily exploited large fishes worldwide, both as a targeted species as well as bycatch, as evidenced by their significant overlap in distribution with global commercial longline fishing (Queiroz et al., 2019). Surprisingly, only a small handful of studies have investigated the response of blue sharks to capture, with the majority of studies looking at survival in response to commercial fisheries bycatch (e.g., Molina and Cooke, 2012). When caught as bycatch in pelagic longlines in the Northwest Atlantic, blue sharks show a consistent 13–15% at-vessel mortality rate (Campana et al., 2016; Gallagher et al., 2014b). Estimates of post-release mortality in these types of studies have ranged from 0% to 33%, with all mortalities occurring in response to capture-related injury (Campana et al., 2016), while another study conducted in the Indo-Pacific documented a 17% post-release mortality rate (Musyl and Gilman, 2018). Blue shark blood physiology may be relatively robust to longline capture for periods ranging from 2 to 12 h (Marshall et al., 2012), but the long soak times (duration of gear deployment) of fisheries gear in fisheries-dependent bycatch studies can render understanding the relationship between hook time (HT; time for which an animal is on the line) and stress difficult. Even less information is known about how blue sharks respond to the process of capture and release under recreational settings, which is surprising given that these interactions occur at a global scale and actually carry a much greater suite of operational, logistical, and angler-related variables that may influence blue shark survival (Gallagher et al., 2017a). Recreational fishing for sharks is increasing, with recreational landings of large sharks (non-dogfish) actually exceeding commercial landings in the United States in some recent years (Gallagher et al., 2017b), and blue sharks represent the most commonly caught pelagic shark species in recreational shark fisheries (Babcock, 2008).

In this study, we evaluated the physiological response of blue sharks to recreational angling off the coast of New England in the Northwest Atlantic. The objectives of this study were: (1) to describe the effects of rod and reel angling on selected stress physiology parameters in blue sharks; and (2) to determine if and how these parameters were affected by fight time and shark size. We hypothesized that the magnitude of physiological stress would be correlated with fight time, and that smaller sharks would be more vulnerable to capture stress. We discuss the findings of this study as they relate to the sustainability of blue shark recreational fisheries interactions, both when targeted or captured as bycatch.

2. Material and methods

This study was conducted in federal waters off Cape Cod and Nantucket (40–42° N, 69–71° W) in southeastern Massachusetts, USA (see Fig. 1). All sampling was conducted between July 1 to September 27, 2019, during the seasonal occurrence of pelagic sharks off the New England coast.

2.1. Shark capture and sampling

The majority of sharks sampled in the study were captured using a stand-up rod and reel set up (Penn Reels 70ST, Penn Reels 130ST International II, and Avet T-RX 80 standard reels), with baits floated from a drifting boat. Penn Reels (130ST International II) were mounted on curved rod butts attached to 150–200 cm rod tips and rigged with 130–250 lb test monofilament fishing line, wire leader consisting of either a 300-cm long, 400–500 lb test wire trace or a 60–150 cm long,

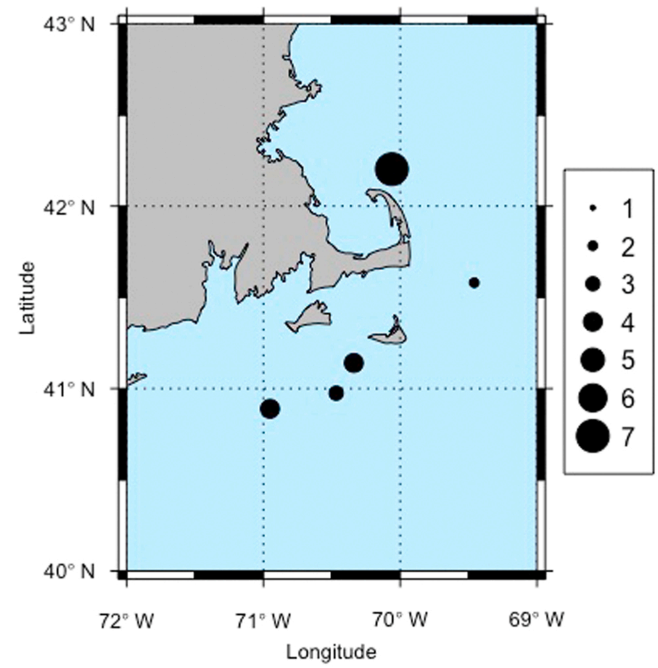

Fig. 1. Capture locations of blue sharks (*Prionace glauca*) sampled in the study. Map of the study area off the coast of Massachusetts, USA. Blue shark (*Prionace glauca*) capture locations are identified with closed circles, with the size of the circle representing the number of individuals caught at each location (see legend).

200–300 lb test single wire leader, and terminated in a 12/0–18/0 gaude circle hook. Avet reels were mounted on straight rod butts attached to 150 cm rod tips and rigged with 200-lb test hollowcore braided fishing line, a 250-lb test monofilament topshot, a 90–250-cm long, 200–300-lb test single wire strand and terminated in a 12/0–18/0 gauge circle hook. Baits consisting of blue fish (*Pomatomus saltatrix*), and Atlantic mackerel (*Scomber scombrus*) were set at varying depths using lead weights (225–400 g) in an effort to attract sharks potentially swimming at different depths throughout the water column. A small subset of sharks (n = 3) was captured using a Daiwa Saltiga Dogfight 8000 h spinning reel mounted on a 225-cm custom-built tuna rod. The spinning reel was rigged with 130-lb test braided fishing line spliced into six meters of 130-lb test fluorocarbon leader line, terminating with two meters of size 14 (~220 lb test) wire and a 14/0 gauge circle hook. This gear is consistent with that commonly used both by recreational anglers targeting sharks and those targeting tuna and billfish who may encounter blue sharks as bycatch. The total HT of each shark was measured using a timer, starting immediately after the shark was hooked and terminating immediately after blood was drawn (see below).

All sharks were reeled to the boat by a team of four anglers, comprising experienced recreational shark anglers, charter staff, and researchers with significant recreational angling experience. Sharks were brought in as quickly as was feasible given the gear and size of the individual animal. Once sharks were brought close to the boat they were landed boatside within one minute, and quickly secured alongside the boat using a tail rope and a cable positioned around the body near the dorsal fin. The duration of this handling is representative of the time needed to secure and de-hook a shark in the recreational fishery. A sample of 7 mL of whole blood was immediately drawn from the caudal vasculature using 18-gauge needles and plastic non-heparinized syringes.

2.2. Blood analysis

Three small aliquots of blood totaling 2 mL were immediately analyzed (< 3 min after draw) for glucose (mmol/L), lactate (mmol^{-1}), and pH. Glucose levels were obtained using a Accu-Chek Glucose meter (Roche Diabetes Care, Inc., Basel, Switzerland). Lactate levels were obtained using a Lactate Plus Meter (Nova Biomedical, Waltham, MA, USA). pH levels were obtained using a HI 99161 pH meter (Hanna Instruments, Woonsocket, RI, USA). The accuracy of these meters has been validated in previous field studies on fish and elasmobranchs (Benson et al., 2019; Cooke et al., 2008; Gallagher et al., 2019; Talwar et al., 2017). Precaudal length (PCL) (distance from the tip of the snout to the origin of the caudal fin), fork length (FL) (distance from the tip of the snout to the fork of the caudal fin), and total length (TL) (distance from the tip of the snout to the end of the caudal fin) were recorded. The shark was sexed and examined for any signs of injury or trauma, and the hook was then removed and the shark was released. The remaining portion of the blood sample (~5 mL) was stored in heparin vials on ice to be later spun down to separate the plasma (12,000 X gravity for 5 min), which was frozen and stored (−20 °C) for further laboratory analysis. Plasma samples were analyzed using a VetScan VS2 at Georgia Aquarium (Atlanta, Georgia, USA) for plasma electrolytes (potassium [K^+], calcium [Ca^{2+}], and phosphate [PO_4^{3-}]). The care and use of experimental animals complied with United States animal welfare laws, guidelines and policies as approved by the National Marine Fisheries Service (Letter of Acknowledgement SHK-LOA-19–02).

2.3. Statistical analysis

We used generalized linear models (GLMs) to evaluate the potential influence of HT, sea surface temperature (SST), and TL on glucose, lactate, pH, Ca^{2+}, PO_4^{3-}, and K^+ (Dapp et al., 2017; Gallagher et al., 2014a; Jerome et al., 2018). We first assessed potential collinearity among independent variables using the R package *usdm* (Naimi et al., 2014). SST values were generally obtained from onboard temperature sensors; however, no such equipment was on board during one sampling day, and as such, SSTs for those sharks were obtained using the nearest NOAA buoy (Station 44097 – Block Island, RI). Outliers were identified and removed using Rosner's test for outliers in the R package *EnvStats* (Millard, 2013). Next, we fit a GLM for each response variable incorporating all three independent variables as predictors, using the R base package *stats* (R Core Team, 2021). Given the number of independent observations (n = 20), we then performed model selection to reduce the potential for overfitting using the R package *MASS* (Venables and Ripley, 2002), by comparing Akaike Information Criteria (AIC) scores for reduced models whereby one term was dropped from the full model. We dropped the term that resulted in the lowest AIC score for the reduced model for each blood parameter. For several analytes (glucose, pH, Ca^{2+}, and PO_4^{3-}), this model selection procedure indicated that the lowest AIC score would have been achieved by dropping HT from the model (retaining SST and TL). However, in all such circumstances, selection of an alternate reduced model which retained HT (i.e., either HT+SST or HT+TL) resulted in a ΔAIC that was < 1 when comparing the two reduced models. As such, and given our interest in HT for this study, in these instances we ran both reduced models (i.e., one which retained HT and one which did not). A complete description of reduced models used for each blood parameter is included as Table 1. We analyzed the significance of predictive factors in the reduced models using likelihood ratio tests in the R package *car* (Fox and Weisberg, 2019). All data analyses were performed in R Studio version 1.4.1103/R version 4.0.4 (R Core Team, 2021) and significance was declared at $\alpha < 0.05$.

3. Results

Twenty male blue sharks were sampled between July 29, 2019 and September 27, 2019 (Fig. 1; Table 2). SSTs during sampling activities ranged from 18.3 °C to 22.8 °C, with a mean of 20.2 ± 0.3 °C (mean ± standard error). Shark TL ranged from 168 cm to 314 cm, with a mean size of 246 ± 9 cm, suggesting that most individuals were adults (Montealegre-Quijano et al., 2014; Pratt, 1979; Skomal and Natanson, 2003). HT ranged from 1 min to 32.5 min, with a mean of 13.3 ± 1.9 min. At the time of landing, fish were observed to be in generally good condition, with no visible evidence of hooking injury (e.g., foul-hooking) or exhaustion. No sharks were gut-hooked during the study. All sharks swam away vigorously and did not exhibit signs of equilibrium loss. The full results from the laboratory analysis of blood and blood plasma are shown in Table 2. Lactate and pH values were not available for a small subset of sharks (n = 5 and n = 4, respectively) due to equipment malfunction.

Table 1
Description of generalized linear model (GLM) model families and predictors for each response variable (blood analytes). HT: Hook Time; SST: Sea surface temperature; TL: Total Length.

Response	Family	Predictors
Glucose	Inverse gaussian	HT + TL
		SST + TL
Lactate	Gamma	HT + SST
pH	Gaussian	HT + SST
		SST + TL
Calcium (Ca^{2+})	Gamma	HT + TL
		SST + TL
Phosphate (PO_4^{3-})	Gaussian	HT + TL
		SST + TL
Potassium (K^+)	Inverse gaussian	HT + SST

Results from our GLM approach suggested that HT was not a significant predictor for any of the blood analytes evaluated during our study (Table 3). Similarly, SST was not associated with any variation in concentrations of blood analytes. We observed a significant relationship between TL and glucose, wherein larger sharks were associated with lower levels of blood glucose (inverse gaussian GLM, $p < 0.01$; Fig. 2). During the model selection process for glucose, we noted a possible interaction between TL and HT; however, given the sample size, we caution this result due to the potential for overfitting of the data. No other significant relationships between predictors and response variables were observed.

4. Discussion

As recreational capture of sharks increases, both via targeted shark fishing as well as bycatch in recreational tuna and billfish fisheries, characterizing the physiological impact of rod-and-reel capture will be key to the development and refinement of effective fisheries management plans (see review by Gallagher et al., 2017b). We focused on a relatively consistent segment of the seasonal population of blue sharks, which are predominantly caught as bycatch in the recreational tuna fishery off coastal Massachusetts, USA. Results suggested that in the temperate Northwest Atlantic, mature blue sharks are relatively robust to recreational fisheries capture using rod-and-reel configurations and short hook/fight times. Indeed, we found no influence of HT on any of the blood analytes evaluated, though we identified patterns which may be useful in making broad recommendations to anglers and adaptive management plans.

In prior work conducted in the same region, minor blood acidoses were observed in blue sharks caught with rod-and-reel gear (Skomal, 2006; Skomal and Chase, 2002). Specifically, HT was shown to correlate negatively with pH and positively with lactate, $K^+$and Ca^{2+} (Skomal, 2006); yet here, we observed no such effects. There are several plausible explanations for these differing results, including the potential effects of size, maturity status, sex, season, sample size and reproductive status. Our study exclusively sampled male blue sharks, the majority of which (75%) would be considered mature (maturity for males achieved at FL of ~180.5–183 cm; Montealegre-Quijano et al., 2014; Pratt, 1979; Skomal and Natanson, 2003). Size has been shown to play a significant role in

Table 2
Complete listing of blue sharks captured and associated blood analyte levels. Outliers in response variables (blood analytes) are indicated with an asterisk (*); outliers were removed from the dataset for analysis. HT: Hook time; SST: Sea surface temperature; TL: Total length.

Date	Shark ID	HT (min)	SST (°C)	TL (cm)	Glucose (mmol/L)	Lactate (mmol/L)	pH	Ca^{2+} (mg/dL)	PO_4^{3-} (mg/dL)	K^+ (mmol/L)
7/29/19	394,574	32.5	21.4	263	5.6	1.9	7.61	11.3	8.6	NA
8/17/19	394,573	15	21	221	6.3	2.6	6.26 *	13.3	6.8	6.2
8/18/19	498,021	16.4	19.9	272	7.2	4.9	7.23	13.8	7.1	5.2
8/18/19	498,022	19.3	19.9	279	6.2	–	7.24	12.9	7.1	6.1
8/18/19	498,054	16.3	20.1	314	5.5	2.1	7.2	13.6	5.9	6.1
8/18/19	498,060	30.4	20.5	282	5.5	3.5	7.16	13.8	6.8	5
8/21/19	394,535	17.4	20.2	285	6.12	1.7	7.43	9.9	4.6	–
8/21/19	394,539	14	19.7	296	5.3	1.7	7.23	13	7.2	7.1
8/21/19	394,548	26.1	21.1	305	5.6	3.4	7.29	13.4	7.3	5.5
9/2/19	394,536	9	22.8	259	7	1.8	7.43	13.5	6.9	5.6
9/2/19	394,537	13	22.8	185	7.4	0.8	7.41	13.3	9.8	–
9/2/19	394,538	1	21.2	168	6.5	0.5	7.53	9.9	4.2	5.6
9/21/19	394,541	8	18.8	213	7.5	1.2	–	9.7	5.5	6.5
9/21/19	394,545	3	18.9	234	6	3.6	–	15.5	8.3	6.3
9/21/19	394,546	11	19.0	208	6.4	2.6	–	12.5	9.3	8.1
9/21/19	394,547	13	19.1	262	6.8	2.4	–	11.2	8.2	–
9/24/19	394,549	6.1	18.3	193	7.9	–	7.59	13.1	7.3	5.7
9/27/19	394,553	13	19	213	8.5	–	6.85	10	11.1	–
9/27/19	394,570	3.2	19.5	224	6.6	–	7.38	7.1	11	–
9/27/19	394,571	2.2	20.2	234	6.7	–	7.38	11.6	10.5	–
Mean		13.33	20.2	245.5	6.59	2.38	7.27	12.11	7.70	6.08

Table 3
Summary outputs and results of likelihood ratio tests for each generalized linear model (GLM). Est: Estimate; Inter: Intercept; HT: Hook time; SST: Sea surface temperature; TL: Total length; LR: Likelihood ratio. Significant values indicated in bold. Nearly significant values indicated with an asterisk (*).

Response	Model	Parameter	Model Output				Likelihood Ratio	
			Est	SE	*t*	p	LR Chi Sq	p
Glucose	HT+TL	Inter	0.0024	0.0071	0.337	0.741	–	–
		HT	0.000083	0.00017	0.488	0.632	0.239	0.625
		TL	0.000083	0.000035	2.411	**0.028**	5.780	**0.016**
	SST+TL	Inter	-0.0157	0.0179	-0.877	0.392	–	–
		SST	0.00083	0.00084	0.979	0.341	0.973	0.324
		TL	0.000094	0.000026	3.552	**0.002**	12.466	**< 0.001**
Lactate	HT+SST	Inter	-1.5642	1.2298	-1.272	0.228	–	–
		HT	-0.0127	0.0071	-1.792	0.098	3.205	0.073 *
		SST	0.1090	0.0643	1.695	0.116	3.419	0.064 *
pH	HT+SST	Inter	6.2697	0.8401	7.463	**< 0.001**	–	–
		HT	-0.0047	0.0054	-0.882	0.395	0.777	0.378
		SST	0.0553	0.0415	1.333	0.207	1.776	0.183
	SST+TL	Inter	6.6731	0.8777	7.6003	**< 0.001**	–	–
		SST	0.0474	0.0402	1.180	0.261	1.393	0.238
		TL	-0.0012	0.0011	-1.131	0.280	1.278	0.258
Ca^{2+}	HT+TL	Inter	0.1039	0.0211	4.924	**< 0.001**	–	–
		HT	-0.00016	0.00045	-0.358	0.725	0.127	0.722
		TL	-0.000078	0.000097	-0.800	0.435	0.640	0.424
	SST+TL	Inter	0.1422	0.0544	2.614	**0.018**	–	–
		SST	-0.0018	0.0026	-0.696	0.496	0.478	0.489
		TL	-0.000096	0.000076	-1.260	0.225	1.597	0.206
PO_4^{3-}	HT+TL	Inter	10.5168	2.9903	3.517	**0.003**	–	–
		HT	0.0056	0.0663	0.084	0.934	0.007	0.933
		TL	-0.0120	0.0140	-0.852	0.406	0.725	0.394
	SST+TL	Inter	13.5939	7.7182	1.761	0.096	–	–
		SST	-0.1611	0.3659	-0.440	0.665	0.1938	0.660
		TL	-0.0109	0.0109	-0.999	0.332	0.9972	0.318
K^+	HT+SST	Inter	-0.0212	0.0332	-0.640	0.537	–	–
		HT	0.00019	0.00025	0.737	0.478	0.545	0.461
		SST	0.0023	0.0017	1.346	0.208	1.905	0.168

capture mortality for blue sharks caught via longline, with smaller individuals more likely to succumb to capture stress (Diaz and Serafy, 2005). Smaller sharks have also exhibited greater physiological disruption for large coastal species captured using modified rod-and-reel gears (Gallagher et al., 2014a). The potential effect of size on stress in blue sharks is underscored by our glucose results (Fig. 2) and, taken with the size-related effects detected in Diaz and Serafy (2005), suggest that smaller blue sharks may likely be more vulnerable to capture stress in the recreational setting. While this is supported by metabolic theory, whereby smaller sharks have higher metabolic rates and thus a more challenging (i.e., expensive) time recovering from respiratory or metabolic acidosis (Gallagher et al., 2014a), we caution that the observed trends in glucose may also be associated with other metabolic factors or ontogenetic variations in diet.

The short HTs (13.33 ± 1.88 min, max HT: 32.5 min) utilized in the present study mirror the actual characteristics of the fishery, wherein blue sharks are usually caught with heavy drag and landed relatively quickly. As such, it is not entirely surprising that we did not observe

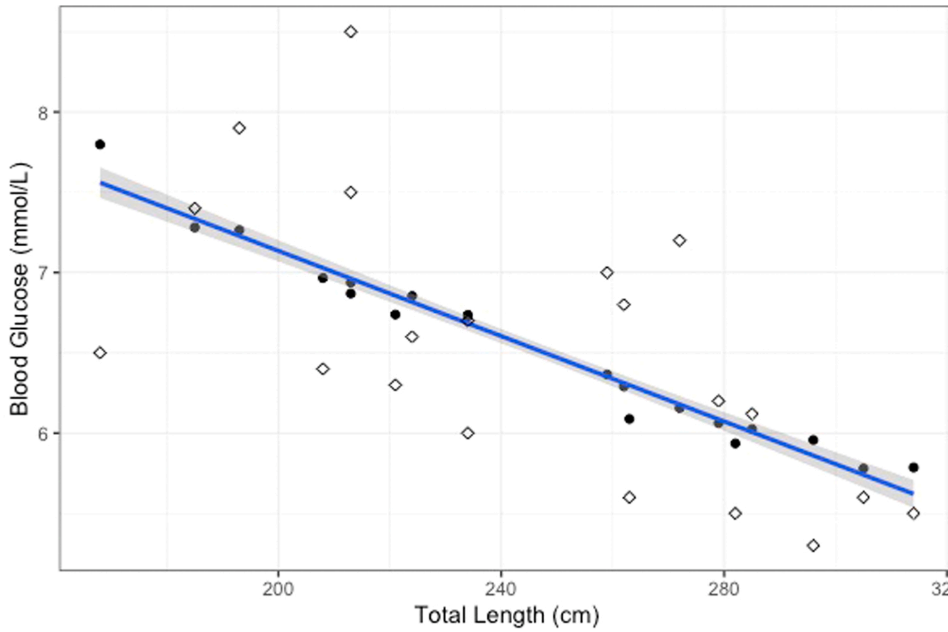

Fig. 2. Blood glucose as a response to total length in rod-and-reel captured blue sharks (*Prionace glauca*). Figure depicts blood glucose as a response to shark total length. Predicted values (closed circles), trendline and confidence interval produced from inverse Gaussian generalized linear model (GLM) using total length (TL) and hook time (HT) as predictors, which identified total length as a significant effect (p = 0.016). Raw glucose values indicated using open diamonds.

consistent physiological effects. Indeed, our HT+SST model for lactate, while not significant at the $\alpha = 0.05$ level, displayed a nearly significant trend of increased lactate at longer HTs (Table 3; Fig. 3), which was a trend observed by Skomal (2006). This is particularly relevant when considering the implications for incidental mortality, as lactate has been shown to be one of the best predictors of mortality in blue sharks caught via longline (Hight et al., 2007; Moyes et al., 2006). Independent of HT, the energy exerted by sharks on the line has also been positively correlated with increased blood lactate in other species (Gallagher et al., 2017a). Therefore, it is likely that blue sharks do not fight to the point of blood acidosis if HTs are minimized under 30 min, a finding which has important implications for maximizing post-release survival for the species.

We note that our sharks were sampled over a relatively narrow range of SSTs (18.2–22.8 °C) relative to their thermal tolerance, and thus any potential effect of SST may have been masked. We encourage future research to sample blue sharks across its thermal range, as SSTs have been observed to influence blood lactate levels in other elasmobranchs (Guida et al., 2016). Similarly, future studies should aim to elucidate any sex-specific variation in the stress response to capture, as sex has been observed to influence mortality rates in longline-captured blue sharks (Coelho et al., 2013) and other species (Butcher et al., 2015; Lotti et al.,

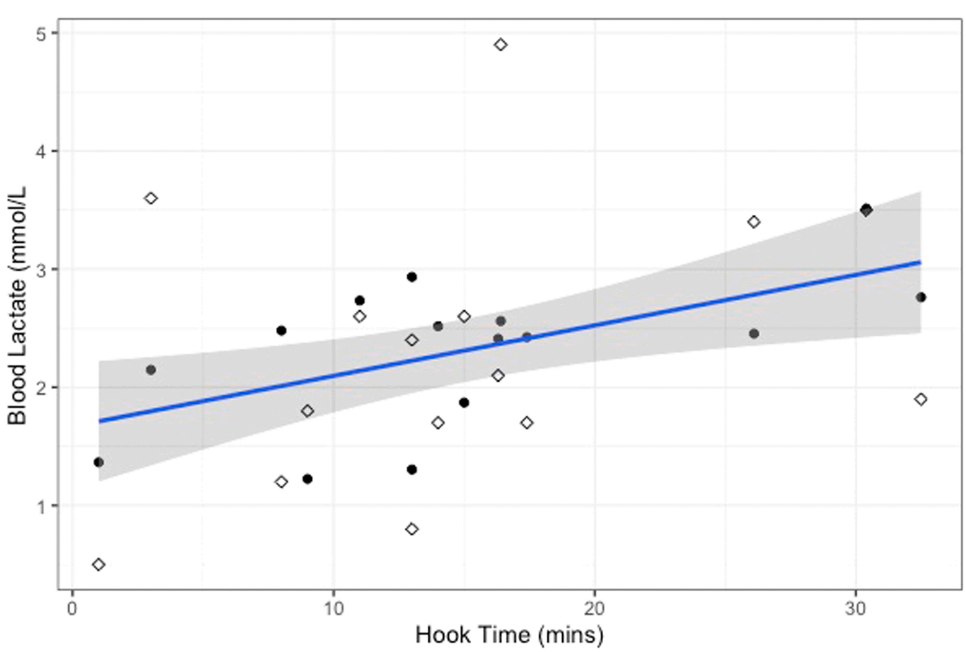

Fig. 3. Blood lactate as a response to hook time in rod-and-reel captured blue sharks (*Prionace glauca*). Figure depicts blood lactate as a response to hook time. Predicted values (closed circles), trendline and confidence interval produced from gamma generalized linear model (GLM) using hook time (HT) and sea surface temperature (SST) as predictors. No significant effects identified. Raw lactate values indicated using open diamonds.

2011), as well as any potential effect of reproductive stage. Finally, future work on capture stress will be improved by concurrently evaluating measures of respiratory acidosis, such as the partial pressure of carbon dioxide, to describe and infer any concomitant respiratory impacts not discerned here. Analysis of ketone bodies and fatty acids may also help discern potential drivers of any observed acidosis, as well as clarify the potential role of diet in the observed size-based variation in glucose levels (Gallagher et al., 2019).

Angler participation in shark fishing has been associated with positive attitudes toward shark conservation (Gallagher et al., 2015), and previous work has shown that, if handled correctly, blue sharks are likely to survive the recreational catch-and-release process (Skomal, 2006). Thus, angler education efforts should be prioritized – including studies such as this where only neglible effects are demonstrated on the study species – as anglers educated on conservation measures are more likely to adopt voluntary fishing practices which minimize harm to captured individuals (Gallagher et al., 2015).

There are inherent challenges with conducting such work. First and foremost, it is difficult to obtain baseline values as fish need to be captured to determine their physiological state. Moreover, from the moment a fish is hooked to when it is blood sampled, there begins a series of physiological changes that occur over different time scales. Some metrics change quickly while others take minutes or hours to reach peak level of alteration (Cooke et al., 2013; Sopinka et al., 2016). In this study we sampled fish immediately upon landing, but we recognize that other study designs can involve sampling fish at a standardized time after landing (e.g., 30 min post landing). Such an approach is difficult with large sharks given the challenges of securing them for long periods in a manner that does not impair their welfare status. This does not devalue the work done here but rather is important contextual information for interpreting our null results (as discussed in Cooke et al., 2013). Nonetheless, the parameters used in this study closely resemble those in the relevant recreational fishing scenarios off New England. Given the range of metrics assessed and the largely null results, our study supports the conclusion that blue sharks captured in the conditions (e.g., SST, fishing gear) described here experience minimal physiological disturbance and are robust to acute capture stressors. Importantly, fish were kept in the water (i.e., no air exposure), and even with the added blood sampling step that would not occur in typical recreational fishing scenarios, the fish were vigorous at time of release.

4.1. Conclusions

Our findings thus support the notion that mature blue sharks in this fishery are likely able to withstand the physical stressors of rod-and-reel capture over relatively short time scales (~30 min or less), a conclusion which is further supported by complementary studies (Campana et al., 2006; Skomal, 2006). We encourage experienced recreational anglers targeting blue sharks to minimize fight times, use circle hooks in order to minimize the chance of gut-hooking (see Willey et al., 2016) and make attempts to remove hooks to minimize future pathological or physical impacts (Borucinska et al., 2002). Responsible catch and release fishing of blue sharks in the Northwest Atlantic thus appears to be a sustainable practice which can be bolstered by additional angler education. Moreover, a sustainable catch-and-release fishery for blue sharks may provide opportunities for community members to engage directly with sharks and in doing so become advocates for shark conservation.

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CRediT authorship contribution statement

Brendan D. Shea: Conceptualization, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Project administration. **Sydney K. Coulter:** Investigation, Data curation, Writing – review & editing, Project administration. **Kelly E. Dooling:** Investigation, Writing – review & editing. **Hana L. Isihara:** Investigation, Writing – review & editing. **Jessica C. Roth:** Investigation, Writing – review & editing. **Elliot Sudal:** Investigation, Writing – review & editing. **Donald J. Donovan:** Investigation, Writing – review & editing, Funding acquisition. **Lisa A. Hoopes:** Investigation, Resources, Writing – review & editing. **Alistair D.M. Dove** Investigation, Resources, Writing – review & editing. **Steven J. Cooke:** Writing – original draft, Writing – review & editing. **Austin J. Gallagher:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The complete dataset associated with this manuscript will be posted on the Virginia Tech Data Respository.

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