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ARTICLE

The Effects of Scallop Dredge Fishing Practices on Physical, Behavioral, and Physiological Stress in Discarded Yellowtail Flounder, Windowpane, and Fourspot Flounder

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Abstract

The Atlantic sea scallop *Placopecten magellanicus* dredge fishery is one of the most lucrative commercial fishing industries in the northeastern United States, and fish bycatch can comprise up to ~42% of the total catch. Benthic species, such as flatfish, are particularly susceptible to unintended capture in scallop dredge gear, and mitigating bycatch and associated mortality has been mandated a priority for fisheries management. Based on this management need, the present study evaluated the physical, physiological, and behavioral stress responses of Yellowtail Flounder *Limanda ferruginea*, Windowpane *Scophthalmus aquosus*, and Fourspot Flounder *Paralichthys oblongus* to capture in the scallop dredge fishery. More specifically, we used generalized additive models and linear regression models to assess the influence of various fishing practices, environmental conditions, and biological factors on injury condition, physiological parameters, and reflex indicators. Although these flatfish species appeared to be physically resilient to capture based on an observable injury assessment, dredge capture and handling factors proved stressful, with the degree of immediate mortality, physiological disturbances, and reflex impairment varying by species. While multiple factors influenced the degree of stress in these species, based on our results the reduction of tow duration and limiting air exposure/sorting duration would likely be the most effective strategies to mitigate the impact of scallop dredge fishing on these flatfish species.

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The incidental capture of nontargeted organisms, referred to as bycatch, is one of the most pressing threats to the world's fish stocks (e.g., Davies et al. 2009). In an effort to mitigate this issue, the 1996 amendment to the Magnuson–Stevens Act mandated "conservation and management measures shall, to the extent practicable, (A) minimize bycatch and (B) to the extent bycatch cannot be avoided, minimize the mortality of such bycatch" (Sustainable Fisheries Act 1996). In response to this legislation, a suite of management approaches, such as annual catch limits and accountability measures, has frequently been employed to reduce fishing pressure on species of particular concern (Alverson 1999; O'Keefe et al. 2014). However, effectively minimizing bycatch mortality remains challenging until underlying causes of such mortality are fully understood (Davis 2002; Gilman et al. 2013).

In general, fishing capture and handling can cause physical injury, physiological and behavioral perturbations, and unobserved postrelease mortality in discarded fish (e.g., Davis 2002). As such, evaluating these often species-specific responses to capture and handling is necessary to establish or refine management measures enabling overexploited stocks to rebuild (Beardsall et al. 2013). From a methodological perspective, vitality indices, such as injury conditions and reflex responses, are commonly employed indicators of fish condition given the broad applicability, low expense, and rapid nature of assessment (e.g., Davis and Ottmar 2006; Davis 2010). For example, a suite of reflexes related to survival can be assessed for presence or absence, and this scoring is summed as a measure of impairment relative to unstressed fish (Davis 2010). Moreover, both injury conditions and reflex responses have been found to be successful predictors of postrelease mortality in numerous fish species (e.g., Barkley and Cadrin 2012; Capizzano et al. 2016; Methling et al. 2017). Additionally, to understand the physiological implications of capture and handling stress, blood stress markers, such as plasma cortisol, glucose, and lactate, can be examined (e.g., Sopinka et al. 2016). Although these markers are not consistently successful predictors of postrelease mortality, they still provide rapid, useful information on the extent to which particular capture variables are stressful on a species (e.g., Davis et al. 2001; Davis and Schreck 2005) and they are widely employed indicators of fish stress (e.g., Forrestal et al. 2017; Methling et al. 2017).

Responses to capture and handling are highly dependent on several factors, including species, gear type, environmental conditions, operational factors, and handling practices (e.g., Davis 2002; Gilman et al. 2013). For example, latency of physiological stress responses (i.e., cortisol, glucose) can be increased in more sedentary species, such as benthic fishes (Vijayan and Moon 1994; Pankhurst 2011), and differences in stress responses (physiological, physical, behavioral) have also been observed among closely related species (Barton 2002; Knotek et al. 2018). Moreover, the severity and type of stress may vary considerably between gear types, for example, with scraping common in traps and exhaustion common in hook-and-line gears (Davis 2002). If a species' response to capture and handling in a given fishery can also be linked to specific, controllable factors (e.g., capture duration, handling practices), best fishing practices may be established and recommended to managers to reduce stress and mortality for released fish, as has been done successfully for other bycatch (e.g., gear modifications, modified handling; Kerstetter and Graves 2006; Stokes et al. 2012; Gallagher et al. 2014; Raby et al. 2015). Given the complex nature of these processes, responses to capture and handling cannot be generalized across species or fisheries, and particular attention should be directed toward species and fisheries of management concern (Davis et al. 2001; Raby et al. 2013).

The Atlantic sea scallop *Placopecten magellanicus* dredge fishery is one of the most lucrative commercial fishing industries in the northeastern United States, and the fishery discards up to ~42% of the total catch as fish bycatch (Benaka et al. 2019). Comprising the third-largest fish bycatch group in the fishery (following only the skate complex and Goosefish *Lophius americanus*), flatfish are particularly susceptible to dredge capture (Benaka et al. 2016). Further, conservative 90% mortality rates are assumed for Windowpane (WP) *Scophthalmus aquosus* and Yellowtail Flounder (YT) *Limanda ferruginea* (Grothues et al. 2017) due to overfished stock statuses (NEFSC 2015), but total mortality has never been formally evaluated for these species in the scallop dredge fishery. When an annual catch limit is exceeded for either species in a stock area, accountability measures are enforced, potentially leading to premature fishery closures in that region, with possible forgone revenue (O'Keefe and DeCelles 2013; Grothues et al. 2017; Winton et al. 2017). Despite the susceptibility to capture and management concern for YT and WP, no studies to date have investigated the effects (i.e., stress, mortality) of scallop dredge fishing capture on any flatfish species. Based on this need, the current study evaluated the physical, physiological, and behavioral stress responses of YT, WP, and Fourspot Flounder (FS) *Paralichthys oblongus* to capture and handling in the scallop dredge fishery. In particular, we investigated the links between abiotic and biotic factors and the observed stress indicators to determine which, if any, fishing factors contributed most to stress and potential mortality in flatfish captured in the scallop dredge fishery. Our results are intended to provide considerations for reducing the impact of the scallop dredge fishery on these flatfish bycatch species.

METHODS

Sampling techniques.— Yellowtail Flounder, WP, and FS were opportunistically sampled during four scallop dredge trips (approximately 6–7 d/trip) on Georges Bank. Research trips occurred from June to October 2017 during a directed Goosefish discard mortality study (A.M.W., unpublished). The fishing gear was a standard New Bedford-style scallop dredge equipped with a steel cutting bar, sweep chain, and steel ring bag. Commercial dredges are 4.57 m in width and have 201-mm rings and a 254-mm-mesh twine top (Yochum and DuPaul 2008). Dredge operations followed standard industry practices, operating both day and night (Yochum and DuPaul 2008). Abiotic sampling was conducted as described in Weissman et al. (2018). In brief, individual tow durations were randomized between 10 and 90 min to encompass the full range of fishery practices. Additionally, while it is important to consider that the collection of true, unstressed "control" specimens is not possible in field studies with towed gear (Mandelman et al. 2013; Morfin et al. 2017), a 5-min tow occurred every 20th tow in an attempt to obtain minimally stressed fish. For all tows, air temperature (°C), tow depth (m), geographic location, and tow duration (min) were recorded. However, the precise amount of time in the dredge bag for each flounder is unknown, and thus tow duration is representative of the maximum possible residency with the gear. Once the contents of the dredge bag were emptied on deck and while the catch was being sorted by fishermen, YT, WP, and FS were collected from the catch for assessment. The duration of air exposure (min) was documented for each sampled fish and was represented by the elapsed time between when the dredge left the water and when the individual fish was assessed. Each sampled fish was measured for TL (cm).

Vitality indicators.— All sampled fish were evaluated for vitality—a protocol that assessed both overt physical injury and reflex impairment (Table 1). An injury condition index developed by Weissman et al. (2018) was used to document the extent of observable trauma (Figure 1). For reflex impairment, a suite of seven reflexes related to survival (Davis 2010; Barkley and Cadrin 2012) was evaluated for presence or absence in each individual. These reflexes were selected because they have been previously linked to postrelease survival in YT (Barkley and Cadrin 2012) and other flatfish species (e.g., Davis 2007; Uhlmann et al. 2016; Methling et al. 2017) and they could be rapidly assessed (<1 min/individual).

Physiological stress exams.— To quantify physiological status at the point of dredge capture and handling, approximately 1 mL of blood was collected from a subset of captured YT, WP, and FS. Blood was extracted from the caudal vein using a heparinized syringe and 26-gauge needle. Glucose, lactate, and hemoglobin concentrations were measured in situ with handheld meters (Glucose Max Plus and Lactate Plus, Nova Biomedical, Waltham, Massachusetts; HemoCue HB 201+, HemoCue America, Brea, California) previously validated for use with teleost blood (Clark et al. 2008; Stoot et al. 2014; Collins et al. 2016). When glucose or lactate concentrations were below the detection limit of the meters, the minimum detection values (20 mg/dL and 0.3 mmol/L for glucose and lactate, respectively) were used. Whole-blood samples were transferred into microcapillary tubes and centrifuged (LW Scientific, Lawrenceville, Georgia) for approximately 4 min to measure hematocrit (packed erythrocyte volume, %). Mean corpuscular hemoglobin concentration was calculated using the ratio of hemoglobin to hematocrit (e.g., Sulikowski et al. 2003). The remainder of whole blood was centrifuged to separate plasma from red blood cells, and the plasma was stored frozen prior to cortisol analyses. In the shoreside laboratory, plasma cortisol concentrations were quantified following a standard radioimmunoassay technique outlined by Weissman et al. (2018), and cortisol antibodies were used in a final dilution of 1 to 2,100. Average hormone extraction recoveries were calculated as 86.1, 81.2, and 84.2% for YT, WP, and FS, respectively. Inter-assay variances were calculated as 9.1, 5.1, and 8.3% for YT, WP, and FS, respectively. Average intra-assay variances were

TABLE 1. Descriptions of vitality indices used to assess the degree of observable injuries and reflex impairment in Yellowtail Flounder, Windowpane, and Fourspot Flounder captured in the commercial scallop dredge fishery. Reflexes were derived from Barkley and Cadrin (2012).

Vitality indicator	Description
	Injury condition
(1) Uninjured	No observable injuries
(2) Minor damage	Torn fins, skin abrasion, mucus damage
(3) Severe trauma	Large lacerations, exposed internal organs
(4) Dead	Unresponsive
	Reflex
(1) Resistance	Dorsoventral movement in response to handling
(2) Mouth	Automatic closing of the mouth after forced opening
(3) Operculum	Automatic closing of the operculum after forced opening
(4) Gag	Gag in response to the insertion of a probe into the throat
(5) Fin control	Resistance to the brushing of fins
(6) Natural righting	Attempt to dorsoventrally right itself within 5 s
(7) Evade	Attempt to actively swim away upon release

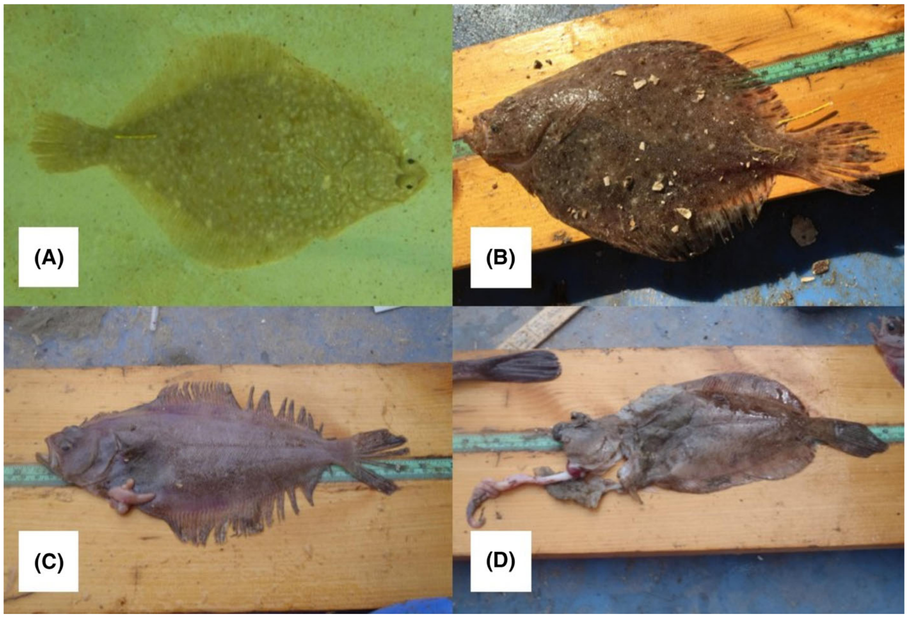

FIGURE 1. Representative examples of injury conditions observed in Yellowtail Flounder, Windowpane, and Fourspot Flounder captured in the commercial scallop dredge fishery: **(A)** an Injury 1 fish, **(B)** an Injury 2 fish, **(C)** an Injury 3 fish, and **(D)** an Injury 4 (dead) fish.

calculated as 5.2, 5.4, and 5.2% for YT, WP, and FS, respectively.

Statistical analysis.— Multivariate generalized additive models (GAMs) for ordered categorical responses were used to determine which, if any, abiotic and biotic factors (tow duration, tow depth, air exposure duration, TL, and air temperature) influenced injury condition and reflex responses. For FS, a multivariate binomial GAM was used to determine the influence of all abiotic and biotic factors on immediate mortality. Additionally, linear regressions were used to determine which, if any, abiotic and biotic factors were influencing each blood physiological stress marker (plasma cortisol, glucose, lactate, hemoglobin, hematocrit, and mean corpuscular hemoglobin concentration). Physiological stress markers were log transformed when evidence of nonnormality of residuals was present. Due to limited sample sizes of physiological stress markers, multivariate models could not be included in the linear regression models. To reduce the likelihood of obtaining a type I statistical error associated with a large number of statistical tests, *P*-values for all statistical tests performed for each species were adjusted using a sequential Bonferroni procedure (Rice 1989). In brief, the sequential Bonferroni procedure adjusts (inflates) all original *P*-values based on the total number of statistical tests performed (Rice 1989). Statistical significance of Bonferroni-adjusted *P*-values was set at $\alpha = 0.05$. All statistical analyses were completed in RStudio (R Core Team, Vienna), and GAMs were completed in the gam package. Detailed results of all statistical analyses are provided in the Supplementary Materials (available separately online).

RESULTS

Characterizing Injury Condition, Reflex Impairment, and Physiological Stress

Only one individual of each species was captured in 5-min tows to serve as minimally stressed fish, and therefore these individuals could not be included in statistical analyses. The minimally stressed YT was categorized as Injury 2 and had four out of seven possible reflexes present, the minimally stressed WP was categorized as Injury 1 and had five out of seven reflexes present, and the minimally stressed FS was categorized as Injury 2 and had four out of seven reflexes present. Of the other 194 fish evaluated (YT, $n = 33$; WP, $n = 39$; FS, $n = 122$), 90.9% of YT, 92.3% of WP, and 73.8% of FS were categorized as uninjured (Injury 1) or had minor injuries (Injury 2; Table 2), while all fish evaluated had some degree of reflex impairment (<7 reflexes present; Table 3). The reflexes most frequently impaired in each species were the evade response, followed by the natural righting response (Table 3). Blood physiological stress parameters varied widely across species and among individuals (Table 4). Blood was also collected from the minimally stressed FS, and blood parameters for this individual are provided in Table 4.

TABLE 2. Percentages (number of individuals in parentheses) of Yellowtail Flounder, Windowpane, and Fourspot Flounder representing each descriptive injury condition captured in the commercial scallop dredge fishery over the course of the study.

Species	Injury 1	Injury 2	Injury 3	Injury 4
Yellowtail Flounder	66.7 (22)	24.2 (8)	6.1 (2)	3.0 (1)
Windowpane	82.1 (32)	10.3 (4)	0.0 (0)	7.7 (3)
Fourspot Flounder	41.8 (51)	32.0 (39)	1.6 (2)	24.6 (30)

TABLE 3. Percentages (number of individuals in parentheses) of Yellowtail Flounder, Windowpane, and Fourspot Flounder with a total of 0–7 reflex responses present, and percentages (number of individuals in parentheses) with each reflex present.

Variable	Yellowtail Flounder	Windowpane	Fourspot Flounder
Total number of reflexes present			
0	6.1 (2)	10.3 (4)	28.7 (35)
1	18.2 (6)	15.4 (6)	28.7 (35)
2	9.1 (3)	20.5 (8)	16.4 (20)
3	27.3 (9)	20.5 (8)	13.1 (16)
4	21.2 (7)	15.4 (6)	10.7 (13)
5	15.2 (5)	12.8 (5)	2.5 (3)
6	3.0 (1)	5.1 (2)	0 (0)
7	0 (0)	0 (0)	0 (0)
Reflex present			
Resistance	57.6 (19)	64.1 (25)	32.8 (40)
Mouth	66.7 (22)	48.7 (19)	35.3 (43)
Operculum	33.3 (11)	64.1 (25)	42.6 (52)
Gag	45.5 (15)	30.8 (12)	27.1 (33)
Fin control	42.4 (14)	35.9 (14)	11.5 (14)
Natural righting	33.3 (11)	20.5 (8)	4.1 (5)
Evade	18.2 (6)	10.3 (4)	2.5 (3)

Effects of Abiotic and Biotic Factors on Stress Indicators

Fish were captured in tow durations ranging from 10 to 90 min and tow depths ranging from 47.6 to 87.8 m. They were air exposed for durations ranging from 1.75 to 30.1 min, with air temperatures ranging from 13.7°C to 30.7°C. Ordered categorical response GAMs suggested that injury condition was affected by abiotic factors in FS; however, the removal of Injury 4 (dead) individuals from the GAM indicated that abiotic factors were not influencing the degree of physical injury for live FS but rather influencing immediate mortality. Therefore, a binomial GAM was used and revealed significant effects of air exposure duration (adjusted $P = 0.015$) and air temperature (adjusted $P = 0.027$) on immediate mortality in FS (Figure 2; Table S.1 available in the Supplementary Materials separately online). No abiotic or biotic factors significantly influenced injury condition in YT or WP (adjusted $P > 0.05$; Tables S.2 and S.3, respectively). Additionally, GAMs indicated that air exposure duration was the only factor with a significant effect on the number of reflexes present in live FS, such that there were significantly fewer reflexes present in FS that were exposed to air for extended durations (adjusted $P = 0.010$; Figure 3; Table S.4). In contrast to FS, reflex impairment was not significantly affected by any abiotic or biotic factors in YT or WP following the sequential Bonferroni correction (adjusted $P > 0.05$; Tables S.5 and S.6, respectively). Linear regressions indicated that blood physiological stress parameters were influenced by abiotic factors in WP (Figure 4). In particular, glucose concentrations were significantly higher in WP exposed to air for longer duration ($F = 23.12$, adjusted $P = 0.017$; Figure 4A; Table S.7), and lactate concentrations were significantly higher in WP captured during extended tow durations ($F = 24.12$, adjusted $P = 0.014$; Figure 4B; Table S.7). Physiological stress parameters were not significantly influenced by any abiotic or biotic factor in YT or FS (adjusted $P > 0.05$; Tables S.8 and S.9, respectively).

DISCUSSION

The majority of fish (80.4%) suffered no (Injury 1) or minimal (Injury 2) observable injuries in the current study, suggesting that these species appear to be physically resilient to capture and handling in the commercial scallop dredge fishery. The results of our study are similar to those of Weissman et al. (2018), who found that approximately 80% of Goosefish captured in the scallop dredge fishery had no or minimal observable injuries using the same condition index. In contrast, the majority of Little Skate *Leucoraja erinacea*, Winter Skate *L. ocellata*, and Barndoor Skate *Dipturus laevis* suffered injuries such as lacerations, hemorrhaging, and/or internal bleeding due to dredge capture (Knotek et al. 2018). Using another towed gear, the commercial otter trawl, Yergey et al. (2012) observed that the majority of Summer Flounder *Paralichthys dentatus* suffered moderate or significant abrasions, scale loss, and mucus damage due to capture in this groundfish fishery. Differences in the degree of observable trauma between flatfish species captured in scallop dredge gear (the present study) and Summer Flounder captured in otter trawl gear (Yergey et al. 2012) may be related to tow duration, gear configuration, and/or catch composition. For example, the shorter tow durations used in the current study (10–90 min) may have minimized the occurrence of severe external injuries compared to otter trawl tow durations (111–129 min) used in the Yergey et al. (2012) study. Additionally, it is possible that fish may be more vulnerable to skin (i.e., abrasions, scale loss) and

TABLE 4. Descriptive results (mean ± SE, range, and *n*) of blood physiological stress parameters for Yellowtail Flounder, Windowpane, and Fourspot Flounder following capture in the commercial scallop dredge fishery (MCHC = mean corpuscular hemoglobin concentration). For reference, the results of blood physiological stress parameters for the single Fourspot Flounder captured in a 5-min tow is provided.

Blood stress parameter	Yellowtail Flounder			Windowpane			Fourspot Flounder			
	Mean ± SE	Range	*n*	Mean ± SE	Range	*n*	Mean ± SE	Range	*n*	5-min tow
Cortisol (ng/mL)	15.9 ± 6.1	1.1–54.8	8	20.0 ± 4.6	1.3–46.6	12	1.9 ± 0.8	0.2–10.9	13	0.4
Glucose (mg/dL)	42.3 ± 7.3	22.5–84.0	8	64.3 ± 6.7	32.0–120.5	14	23.8 ± 3.4	20.0–64.5	13	20.0
Lactate (mmol/L)	1.0 ± 0.2	0.3–1.9	8	2.7 ± 0.4	0.3–4.6	14	1.4 ± 0.2	0.3–2.7	13	0.3
Hemoglobin (g/dL)	5.2 ± 1.1	0.6–8.6	8	4.1 ± 0.2	2.2–5.7	14	5.3 ± 0.3	3.7–6.9	13	4.65
Hematocrit (%)	42.0 ± 10.0	2.5–92.0	8	34.5 ± 4.3	13.0–74.0	13	26.9 ± 2.1	11.0–42.0	13	21.0
MCHC (g/dL)	16.1 ± 2.9	5.2–30.0	8	13.4 ± 1.4	7.6–24.1	13	21.1 ± 2.0	11.9–42.3	13	22.1

mucus damage when entrained in the twine mesh of an otter trawl cod end (Broadhurst et al. 2006) compared to the smoother metal rings of a scallop dredge bag. These fisheries also differ in catch composition, which may impact the severity of injuries of captured organisms (Gilman et al. 2013); the otter trawl fishery is dominated by northeast groundfish (i.e., Haddock *Melanogrammus aeglefinus*, Pollock *Pollachius virens*, and Atlantic Cod *Gadus morhua*), Spiny Dogfish *Squalus acanthias*, skates, and flatfish, whereas the scallop dredge fishery is dominated by Atlantic sea scallops and other invertebrates, skates, Goosefish, and flatfish, and likely higher proportions of substrates than the otter trawl fishery (Harrington et al. 2005).

Although physical injury was generally minimal in the current study, immediate mortality was affected by fishing factors in FS. For example, at-vessel mortality was significantly influenced by air exposure duration in FS, such that mortality increased with increasing air exposure. It is possible that the increased mortality associated with increasing air exposure duration was related to the sorting process in addition to air exposure. In particular, extended interaction with catch biomass (i.e., flatfish were occasionally observed to be bitten by Goosefish or buried under the catch) or other stressors (i.e., fishermen handling practices) occurring during the scallop dredge fisheries' sorting process may have contributed to mortality. The significant influence of air exposure duration (or sorting duration) on immediate mortality is unsurprising, as time on deck is often found to be a significant predictor of mortality in other flatfish (e.g., Richards et al. 1995; Ross and Hokenson 1997). In addition to air exposure duration, immediate mortality of FS was also significantly influenced by air temperature, such that mortality increased with increasing air temperature. Air temperature has also been found to be a significant contributor to mortality in American Plaice *Hippoglossoides platessoides* (Ross and Hokenson 1997), and while not directly comparable, increased gradient between bottom water and air temperatures influenced mortality in Little Skate (Knotek et al. 2018). Collectively, our results suggest the scallop dredge fishery sorting process (including air exposure and air temperature) has a significant influence on immediate mortality in FS.

While not always predictive of mortality, blood physiology may provide a relative indicator for the degree to which fishing gear types or capture variables are stressful on a species (Davis et al. 2001; Davis and Schreck 2005). Indeed, multiple blood physiological stress parameters were significantly affected by abiotic factors in WP, and these relationships may provide insight into the capture and handling factors that proved stressful in this species. For instance, glucose concentrations were significantly higher in WP that were exposed to air for extended durations. This finding was unsurprising, as the mobilization of energy reserves needed to support anaerobic metabolism has been observed as a hyperglycemic response in several teleost species during air exposure (e.g., Barton 2000; Davis and Schreck 2005; Beardsall et al. 2013; Uhlmann et al. 2015). In addition, blood lactate concentrations were significantly higher in WP that were captured in longer tow durations. The transition to anaerobic metabolism and associated accumulation of lactate within the bloodstream are known to occur when fish receive minimal or no oxygen (e.g., Pankhurst 2011; Sopinka et al. 2016), including during capture and handling stressors, such as exhaustive exercise (Kieffer 2000), air exposure (Cicia et al. 2012), and obstruction of ventilation (Gilman et al. 2013). As such, extended tow durations likely increased exercise exhaustion and/or suffocation (from lack of oxygen in towed gear with large catches; Gilman et al. 2013) during dredge capture, and it appears that these exacerbated stressors resulted in metabolic acidosis in WP. Based on these relationships between abiotic factors and blood physiological stress parameters, extended capture duration and air exposure represent important stressors to WP in the commercial scallop dredge fishery.

Acute physiological stress from fishing capture and handling often inhibits the normal behaviors of released fish (e.g., Beardsall et al. 2013; McLean et al. 2016). In

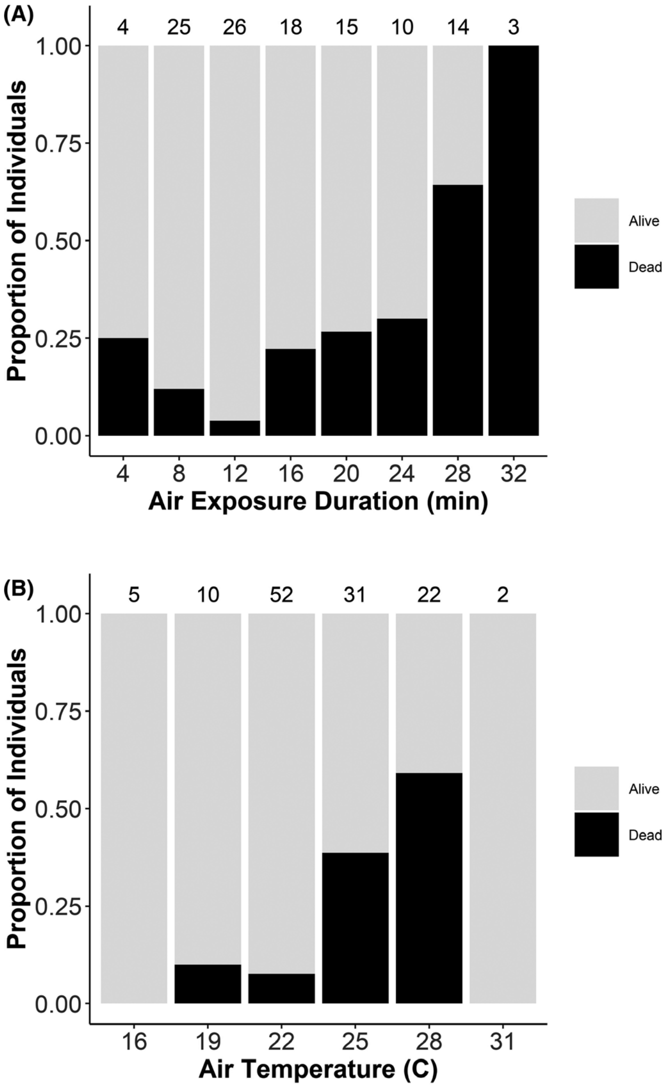

FIGURE 2. The significant effects of abiotic factors on the immediate mortality of Fourspot Flounder captured in the scallop dredge fishery: **(A)** the proportion of individuals in each injury condition binned by 5-min air exposure duration intervals; and **(B)** the proportion of individuals in each injury condition binned by 3°C air temperature intervals. Numbers above bars represent sample size.

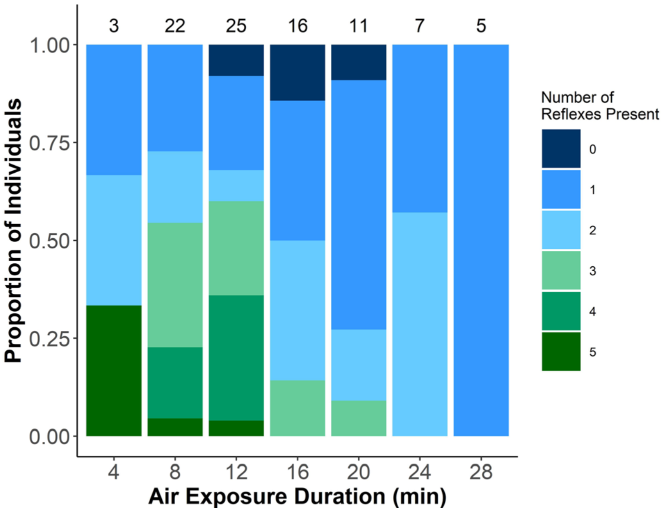

FIGURE 3. The significant effect of air exposure duration on the number of reflex responses in live Fourspot Flounder captured in the scallop dredge fishery. The proportion of live individuals in each reflex response group is binned by 4-min air exposure duration intervals. Numbers above bars represent sample size.

the current study, reflex impairment (<7 reflex responses present) was observed in 100% of YT, WP, and FS, indicating that all sampled individuals suffered unfavorable behavioral effects due to capture and handling in the scallop dredge fishery. Because loss of reflex responses is typically a good predictor of stress and/or postrelease mortality (Davis 2007, 2010), these results suggest possible physiological compromise and even potential mortality (albeit postrelease mortality was not measured). Indeed, the most commonly impaired reflexes in our study were the evade and natural righting responses, and these reflexes were impaired in the vast majority of individuals. Given that orientation and swimming abilities are critical to predator evasion (Davis 2002, 2010; Ryer 2002), the prevalence of these reflex impairments raises concern for the survival of discarded flatfish. Based on our findings and observations of postrelease predation on Goosefish in the scallop dredge fishery (A.M.W., unpublished data), research into postrelease predation and/or mortality rates of flatfish in this fishery is warranted and could be accomplished using acoustic telemetry, as has been done successfully for other teleost fish species (e.g., Cooke and Philipp 2004; Yergey et al. 2012).

Air exposure duration was the only fishing factor that significantly influenced the number of reflexes present in live FS, such that fewer reflexes were present in FS exposed to air for extended durations. Additionally, a trend of decreasing reflexes present with increased air exposure duration was observed in YT (although this trend was not statistically significant following Bonferroni correction). Similarly, extended bouts of air exposure caused more severe reflex impairment in several fish species in previous studies, including Winter Skate (Knotek et al. 2018) and Goosefish (Weissman et al. 2018) caught in scallop dredge gear and YT (Barkley and Cadrin 2012) and European Plaice *Pleuronectes platessa* (Uhlmann et al. 2016; Methling et al. 2017) caught in trawl gears. Based on these comparisons, it appears that air exposure or other sorting process stressors contributed to behavioral impairment in FS (and to a lesser extent, YT) captured in the scallop dredge fishery. Given the association between behavioral impairment and mortality in many fish species (Davis 2007, 2010), the sorting process may contribute to postrelease mortalities in these flounder.

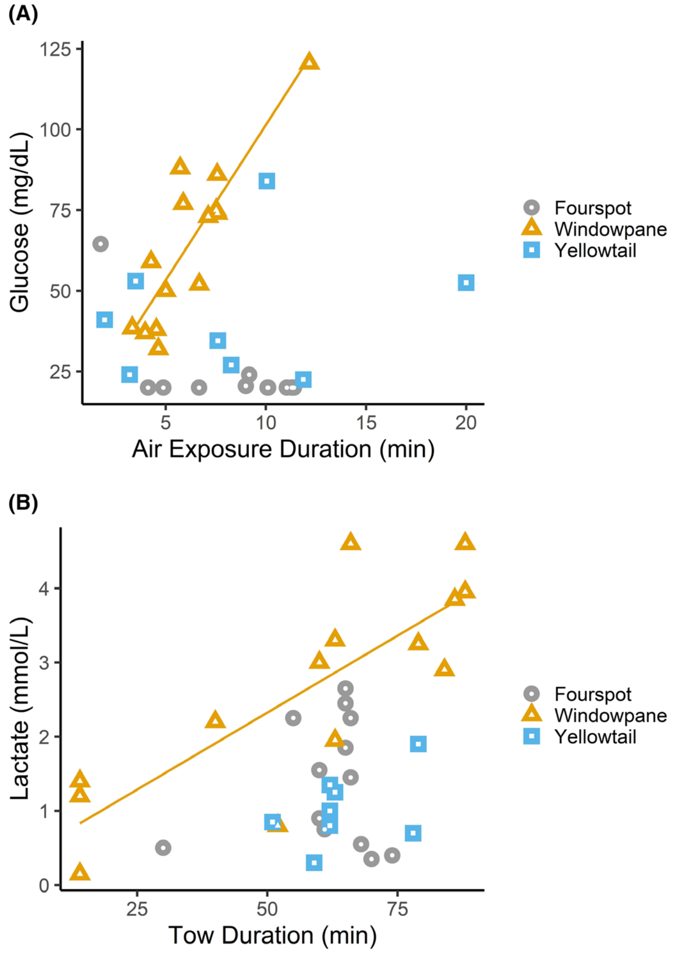

FIGURE 4. The significant effects of abiotic factors on the blood physiological stress parameters in Windowpane (triangles) captured in the scallop dredge fishery. Linear regressions are plotted for statistically significant relationships observed in Windowpane (lines): **(A)** the effect of air exposure duration (min) on glucose concentration (mg/dL); and **(B)** the effect of tow duration (min) on lactate concentration (mmol/L). Note that nonsignificant relationships are plotted for Yellowtail Flounder and Fourspot Flounder for comparison.

Conclusions

Collectively, the results of this study suggest that while YT, WP, and FS suffer minimal observable injuries, capture and handling in the commercial scallop dredge fishery negatively impact these species based on physiological and behavioral indicators of stress. This study also identified multiple capture and handling factors that affected the degree of stress in these species. While the direct sources of stress varied among species, tow duration and air exposure duration (or sorting duration) are operational factors that may be most effectively controlled in the scallop dredge fishery to minimize stress, at-vessel mortalities, and potential postrelease mortalities in flatfish bycatch. For example, shorter tow durations may reduce exhaustive exercise and catch biomass, thereby reducing crushing in the dredge bag and time on deck (due to reduced sorting times). Moreover, reducing air exposure by prioritizing the discarding of flatfish bycatch immediately after capture may minimize the sublethal and/or lethal effects of the sorting and handling process. As such, it is recommended that tow duration and air exposure duration be considered to minimize the impact of scallop dredge fishing on flatfish while maintaining desired target catch rates. However, the success of stress and mortality mitigation for flatfish bycatch will depend upon the adoption of these best practices by scallop dredge fishing crews.

Because the sublethal consequences observed in this study may ultimately lead to unfavorable changes in behavior, reproduction, and survival, understanding these responses to capture and handling is important for assessing the effects of fisheries on discarded species (Wilson et al. 2014). Although this study provides an important first insight into the stress and immediate mortality incurred in YT, WP, and FS due to scallop dredge capture and handling, future research into the postrelease survival outcomes is needed in order to more fully understand the impact of the scallop dredge fishery on these species. Of particular concern is the prevalence of orientation and swimming impairment in these species, which may increase predation risk and negatively impact survival following discarding. Such research will be critical to creating accurate stock assessments and appropriate fisheries management plans for these species, particularly for the overfished YT and WP stocks.

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SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.