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ARTICLE

Condition and postrelease mortality of angled Northern Pike temporarily retained on stringers

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Abstract

Objective: Anglers typically use stringers to keep fish intended for harvest from spoiling or for high-grading purposes (i.e., culling). However, relatively few studies have examined the effects of temporary stringer retention on the physical condition and postrelease mortality of fish. In this study, our objective was to investigate the lethal and sublethal effects of temporarily retaining Northern Pike *Esox lucius* on stringers.

Methods: We evaluated the blood physiology, reflex impairment, injury, and fate of 168 Northern Pike that were exposed for 2 h on one of five treatments: (1) cord stringer through the operculum, (2) cord stringer through the lower jaw, (3) metal stringer through the operculum, (4) metal stringer through the lower jaw, and (5) aerated tank control.

Result: Immediately after retention, blood lactate concentrations of stringer treatments were on average 42% greater relative to controls. Fish from the stringer treatments exhibited injuries of varying severity, most of which (e.g., gill lesions, expanded puncture wounds, swelling) were still present on surviving fish 48 h later. Reflexes were impaired for all stringer fish, whereas control fish tended to have all reflexes intact. No fish died during the treatment period. The highest occurrence of mortality was within the first 8 h following retention for the cord–operculum (48%), metal–jaw (15%), and metal–operculum (19%) treatments. Stringers placed through the operculum had a higher mortality rate (37%) compared with stringers placed through the lower jaw (17%), regardless of stringer type. Overall, 27% of fish placed on stringers died and 68% of the remaining fish showed injuries related to stringers, while control fish showed low mortality (7%) and no meaningful injuries.

Conclusion: Our results suggest that holding fish on stringers causes stress and injury levels that can result in postrelease mortality. As such, fisheries managers should consider restricting the release of fish placed on stringers, and once placed on a stringer, fish should be regarded as part of the daily harvest limit for a given angler.

KEYWORDS

catch limit, culling, *Esox lucius*, harvest, high-grading, stringer

INTRODUCTION

Impact statement

This research highlights the detrimental effects of releasing Northern Pike off stringers during culling. We discovered that this practice results in stress, injury, and frequently death in released fish. We encourage fisheries managers to consider implementing regulations explicitly disallowing this practice to avoid negative impacts on fish populations.

Recreational fishing is enjoyed by an estimated 10.6% of the global industrialized population (Arlinghaus et al. 2015). Although some fish are harvested (e.g., for food; Cooke et al. 2018; Nyboer et al. 2022), even more fish are released to comply with regulations (i.e., slot size, retention limits, season closures) or due to angler conservation ethic (Wydoski 1977; Cooke and Schramm 2007). When practicing selective harvest or high grading, there are situations where retained fish may later be released, such as when a more desirable fish is caught and there is a limit on harvest (Quinn 1996). As such, any deleterious effects of the retention gear and treatment that would have been irrelevant had the fish been harvested—such as gill damage and physiological stress—are now affecting the welfare and potential fitness of the released fish. While these fish may appear to swim away once released, their final fate often remains unknown (Arlinghaus et al. 2007; Coggins et al. 2007).

Retention gear can be used by harvest-oriented anglers to keep their catch “fresh” by keeping the fish alive until the angler is ready to kill and clean the fish. While aerated live wells (e.g., Plumb et al. 1988) or large keep nets (e.g., Raat et al. 1997) are the standard for holding fish in some competitive angling events, harvest anglers also use other, more affordable gears, such as fish baskets and stringers, that can be used from boat or shore (Davie and Kopf 2006). Of the different retention gears available to anglers, stringers are both particularly invasive (the fish being physically held by a stringer fed through their operculum or bottom jaw) and inexpensive (stringers are often found in beginner tackle kits).

Fishing regulations vary by state and province and are often vague around retention. For example, the current fishing regulations in Ontario allow Walleye *Sander vitreus*, Northern Pike *Esox lucius*, Smallmouth Bass *Micropterus dolomieu*, and Largemouth Bass *Micropterus nigricans* to be held and released from a boat when using a live well, but there is no language about retention gear regulations when shore fishing. In Manitoba, there is no language disallowing any specific retention gear in any context, only that fish should be released unharmed if held, which is vague. In Minnesota, anglers are actively encouraged not to release fish (but not outright prohibited) that have been placed on a stringer, but culling is still allowed until anglers reach their daily harvest limit. In contrast, the state of Wisconsin expressly prohibits culling (except under permit in black bass *Micropterus* spp. tournaments), and any fish taken into one's possession (which would include fish placed on stringers) counts toward one's daily harvest limit. Overall, a brief review of relevant regulations revealed that stringers are rarely mentioned in recreational fishing regulations. Previous research has studied the effects of different types of retention gear by examining the consequences of Common Carp *Cyprinus carpio* retention in carp sacks (Rapp et al. 2012), Bluegill *Lepomis macrochirus* held with different methods after ice fishing (Grausgruber et al. 2021), and Bluegill held in fish baskets (Hoxmeier and Wahl 2009). However, while stringers are widely used by recreational harvest anglers, few studies have investigated the immediate and delayed effects of this retention method on game fish. Cooke and Hogle (2000) investigated the effect of fish baskets, keep nets, and stringers on the fate of Smallmouth Bass and found high mortality and injuries from stringers compared with control groups. Further, Chong et al. (2021) studied culling methods used on Largemouth Bass for identification within tournament live wells, including the use of metal through-the-jaw stringer clips. They found that fish treated with stringer clips in the live well had lower blood plasma cortisol, lactate, and glucose compared with fish that were identified with a lasso, mesh bag, or pincher.

Here, we build on all previous research by applying the same four stringer treatments as Cooke and Hogle (2000) to Northern Pike. Northern Pike are one of the three most harvested species in Canada (Fisheries and Oceans Canada 2019), are widely distributed in north temperate regions in North America and Europe, and have been found to be relatively resilient to catch and release (e.g., Arlinghaus et al. 2009; Louison et al. 2017; Bieber et al. 2022). Moreover, they tend to be carefully managed (e.g., using harvest restrictions) such that culling is not uncommon (Paukert et al. 2001). As such, Northern Pike are an ideal species to use to investigate the effects of retention by stringers. To that end, we focus on assessing the sublethal (blood physiology and reflex impairment) and lethal (postrelease mortality) effects of being held on stringers affixed to a boat for 2 h and subsequently monitored for 48 h in holding pens.

METHODS

Study site

All data were collected at the Queen's University Biological Station on Lake Opinicon in southeastern Ontario, where there are no current size limits on Northern Pike harvest. This shallow, eutrophic lake has a maximum depth of 11 m, with half the lake less than 5 m deep (Keast et al. 1978). This study was performed in June of 2022.

Stringers

Two types of stringers were used in this study: a thin metal clip chain stringer and a 0.64-cm braided polypropylene cord stringer fitted with a nail spike. These were chosen to represent two popular market choices used by recreational anglers, at two different price points. While both stringers are readily available for commercial purchase, the cord stringer can also be fashioned quite easily with only a few materials. Both stringers can be attached to the fish either through the operculum opening or by puncturing the skin around the lower jaw (Figure 1). Two fish were placed on each stringer—the thin metal stringer had separate clips for each fish, while fish on the cord stringers were held by the same section of cord.

Treatments

Northern Pike were angled by rod and reel with a variety of lures and were brought to the boat and netted within 20 s. Any deeply hooked or gill-hooked fish were excluded from the study or used as a blood baseline. After hook removal, the total length of each fish was measured to the nearest millimeter, tagged with an anchor tag (Floy Manufacturing) for individual identification, and inspected for any fin and body damage. Fish were randomly assigned to one of six treatments: (1) cord–operculum stringer (CO), (2) cord–jaw stringer (CJ), (3) metal–operculum stringer (MO), (4) metal–jaw stringer (MJ), (5) tank control (TC), or (6) baseline blood (BB) (Figure 1). Blood was taken from baseline fish immediately before being measured or tagged in order to receive the most accurate readings before inducing handling stress within 3 min of capture (Lawrence et al. 2018), after which the fish was released. Fish assigned treatments 1–4 (stringers) were kept in a 378-L aerated tank for a maximum of 90 min (average of 23 min) until a second fish was caught, at which point they were placed together in the water with the stringer secured to the boat. Northern Pike remained on the stringer in the water for exactly 2 h, during which time the boat drifted. Any boat movements by engine were recorded and only occurred when absolutely necessary, for short durations, and at extremely low speeds. For the fifth treatment (control), the fish were held in the tank for 2 h after being angled.

After 2 h, all fish were first tested for two reflex impairments: righting reflex and tail grab. Righting reflex (i.e., equilibrium) assessment involved turning the fish upside down, with a positive response characterized by the fish righting itself within 3 s (as is standard in reflex action mortality predictor testing; e.g., Bower et al. 2016). The tail grab test involved firmly grasping or pinching the caudal peduncle of the fish, with a positive

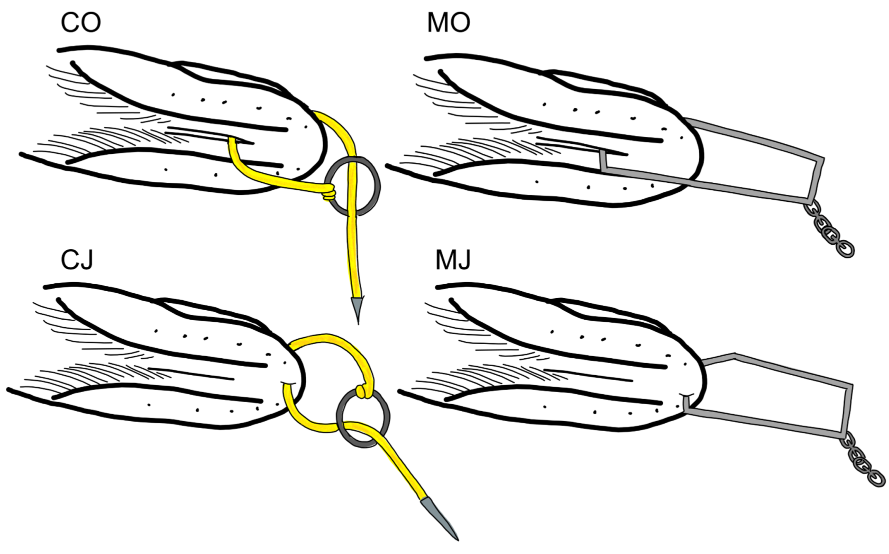

FIGURE 1 Ventral view of stringer positions and material on Northern Pike. Treatment was administered to angled Northern Pike from Lake Opinicon in June 2022, with stringer treatment codes as follows: cord–operculum stringer (CO), metal–operculum stringer (MO), metal–jaw stringer (MJ), and cord–jaw stringer (CJ).

response characterized by the fish bursting away from the touch. To avoid observer bias, all fish were evaluated by the same person, and any uncertainty over whether a response was positive (scored 1) or absent (scored 0) would be marked as an absent response. The presence or absence of these reflexes have been established to indicate vitality of fish and predict fate in a number of game fish (Davis 2010; Raby et al. 2015). Fish were then held in a padded, freshwater-filled trough for blood sampling (Lawrence et al. 2020). Blood (2 mL) was taken from the caudal vasculature of each fish with a 4-mL heparinized vacutainer and a 21-gauge needle and immediately analyzed for glucose (mmol/L; Accu Check Compact Plus, Roche Diagnostics, Basel, Switzerland) and lactate (mmol/L; Lactate Plus, Nova Biomedical Corporation). Both of these devices have been validated for use on fish (Stoot et al. 2014). Injuries from stringers were qualitatively described for each surviving fish immediately and after the 48-h holding period (using standard descriptors employed later in injury scoring; Table 1).

Posttreatment monitoring

After each treatment and blood draw, all fish were held in two aerated tanks (378 L each) on the boat (average of 2 h) with water exchange approximately every hour until they could be brought to a holding pen in the lake.

Fish were kept in two holding pens (175 × 85 × 125 cm, Vexar net material with 1.5-cm mesh) in a shallow, protected bay of Lake Opinicon (Figure 2A). Mortality of each group was assessed at 24 h, and at 48 h each group was assessed for mortality, reflex impairment (equilibrium and tail grab), and injury progression and given an injury score based on damage by the stringer (i.e., puncture wound, bruising, or gill damage; Table 1).

Throughout this study, 11 fish were lost from the holding pen due to small holes forming or predation by birds. These fish were excluded from status and injury score analysis as no conclusion could be made on their fate after 48 h, although their blood glucose, blood lactate, and initial reflex scores were included in the analysis.

Statistical analysis

All statistical analyses were performed using R Statistical Software (version 4.1.2; RStudio Team 2022). The packages coin (Hothorn et al. 2006), survival (Therneau 2022), and AiCcmodavg (Mazerolle 2020) were used. Blood glucose and blood lactate data were first tested with a Kruskal–Wallis test to analyze differences of variance between all treatments and then with a Wilcoxon rank-sum test with continuous correction to determine specific differences between each treatment. The Kruskal–Wallis test was also used to test whether treatment temperature, fish body size, or holding time affected the blood readings. These tests were chosen due to the lack of normality (left skewness) in both blood glucose and blood lactate data, as all attempts of transformation for normality failed.

Because injury score was treated as an ordinal variable, we utilized an extended Cochran–Armitage test for associations between treatment and injury score. A Cox proportional hazards regression was done to test for associations between treatment and rate of mortality (dead in less than 8 h, dead between 8 and 24 h, dead between 24 and 48 h). In addition, a Kaplan–Meier survival curve was fitted to assess mortality over time.

Pearson's chi-square tests and Fisher's exact tests were used to test for differences in reflex impairment scores at time zero between treatments. Among individuals that survived, paired Student's *t*-tests were utilized to determine whether reflex impairment significantly changed, comparing the reflex score immediately after treatment and the reflex score ~48 h later.

Final status (dead or alive) was modeled with eight generalized linear mixed-effect models with binomial

TABLE 1 Injury scores, mortality status, and description of injury. Injury scores were used to describe the condition of Northern Pike angled from Lake Opinicon in June 2022, 48 h after being held on different retention treatments.

Injury score	Explanation
1	Alive at 48 h, no injury.
2	Alive at 48 h, slight injury. Small expansion of puncture hole, slight tissue or gill damage.
3	Alive at 48 h, moderate injury. Expansion of puncture hole, moderate tissue or gill damage. Some swelling of lower jaw.
4	Alive at 48 h, extreme injury. Large expansion of puncture hole, obvious and serious tissue or gill damage. Major swelling and redness of lower jaw.
5	Dead within 24–48 h.
6	Dead within 8–24 h.
7	Dead in less than 8 h (dead in tank—never placed in holding pen).

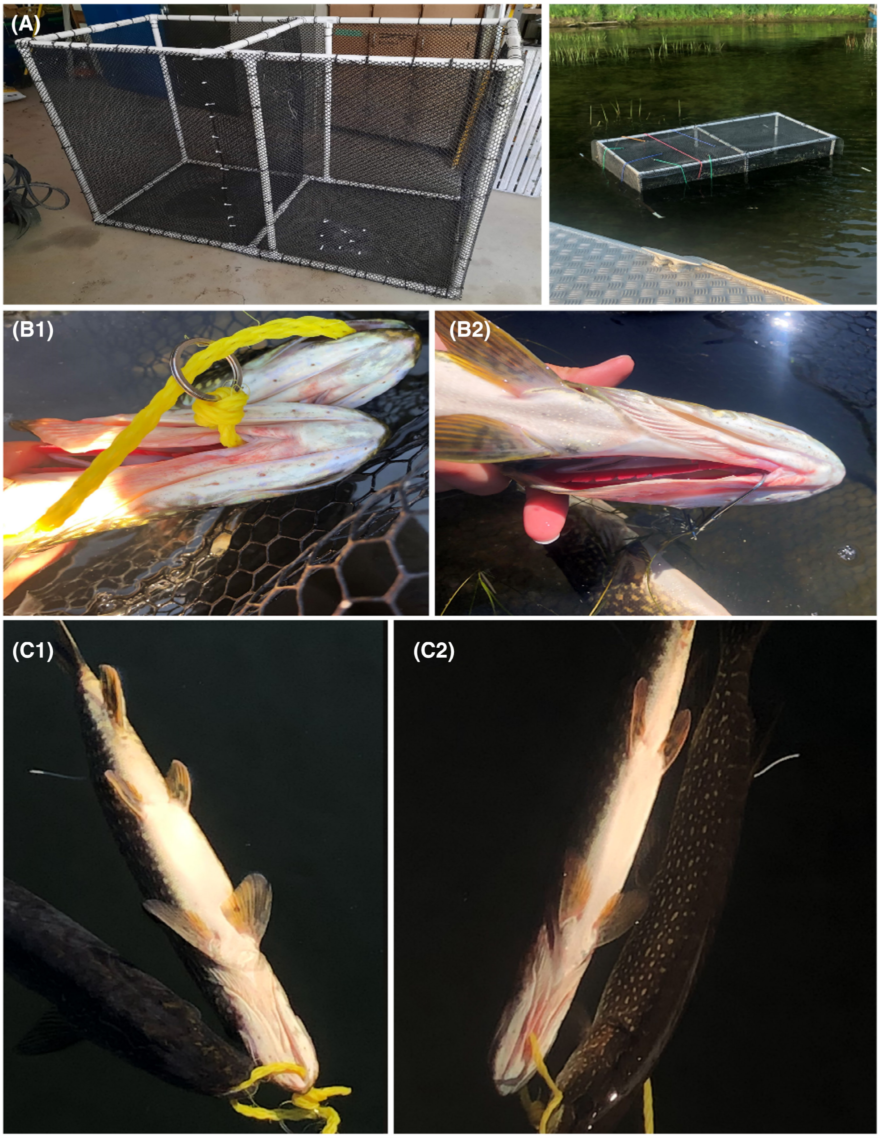

FIGURE 2 Field photos of the stringer study on Northern Pike angled from Lake Opinicon in June 2022, showing (A) one of two holding pens used to hold Northern Pike during the study. Pens were made with Vexar material and PVC pipe and secured with bungee cords and placed in a shallow bay in Lake Opinicon. Row (B) shows swelling and bruising after treatment of (B1) cord–operculum and (B2) metal–operculum stringers. Row (C) shows Northern Pike at the end of the 2-h treatment period of (C1) cord–jaw and (C2) cord–operculum stringers, with swelling and bruising observed only in the cord–operculum treatment.

family distribution and scored with an Akaike information criterion corrected for small sample size (AIC_c). Explanatory variables included treatment, fish total length (mm), average water temperature over the treatment time (°C), boat movement (number of times the boat had to be moved by motor during the 2-h treatment period), stringer material (cord versus metal), and stringer location (lower jaw versus operculum). Interactions were included wherever logical, and all models had stringer pair included as a random effect. The small-sample-size correction was used as the highest-ranking model had a large number of parameters relative to the sample size ($n/K < 40$), and models were considered significant with a $\Delta AIC_c \leq 2$ (Burnham and Anderson 2004).

Finally, we used a one-way analysis of variance to test for differences in body size between treatments. All tests were considered significant at $\alpha \leq 0.05$. All values are presented as mean ± standard deviation.

RESULTS

In total, 168 Northern Pike were captured over 2 weeks. The mean ± SD total length of all fish captured was

517 ± 56 mm (range = 310–689 mm), which was similar across treatments ($F_{5,162} = 0.281$, $p = 0.923$).

Blood physiology

All stringer fish had significantly higher blood lactate levels compared with the control (TC: 11.4 ± 2.75 mmol/L; CO: 16.2 ± 1.61 mmol/L, Wilcoxon rank-sum test [W] = 646, $p < 0.001$; CJ: 16.2 ± 1.01 mmol/L, $W = 693$, $p < 0.001$; MO: 16.4 ± 1.14 mmol/L, $W = 647$, $p < 0.001$; MJ: 15.9 ± 2.30 mmol/L, $W = 643$, $p < 0.001$), while only the metal–operculum ($W = 451$, $p = 0.039$) and cord–jaw ($W = 536$, $p = 0.003$) treatments had significantly higher blood glucose levels compared with the control group (Figure 3). On average, fish in the stringer treatments (16.2 ± 1.54 mmol/L, 6.2–20.0 mmol/L) had blood lactate readings eight times higher than the baseline blood readings (2.9 ± 1.6 mmol/L, 0.4–6.9 mmol/L), with fish in the tank control (11.4 ± 2.8 mmol/L, 7.8–15.8 mmol/L) being five times higher than the baseline. Blood glucose and blood lactate readings were unaffected by either body size (Kruskal–Wallis H-test[88] = 87.1, $p = 0.516$ and H[88] = 86.8, $p = 0.508$, respectively) or average tank temperature (H[45] = 47.5, $p = 0.31$ and H[45] = 62.5, $p = 0.072$, respectively). Time held on the boat before treatment had no effect on blood lactate (H[51] = 56.7, $p = 0.27$), blood glucose (H[51] = 45.9, $p = 0.67$), or final status ($p = 0.625$).

Reflex impairment

All treatments except for MO had significantly lower reflex impairment scores after treatment compared with the control (CO: $p < 0.001$; CJ: $p < 0.001$; MO: $p = 0.06$; MJ: $p < 0.001$; Figure 4A). Paired Student's t-tests showed that all treatments except for the control had significantly improved reflex scores 48 h after treatment, if they survived to 48 h (CO: $t_{19} = -7.4$, $p < 0.001$; CJ: $t_{19} = -7.4$, $p < 0.001$; MO: $t_{33} = -4.9$, $p < 0.001$; MJ: $t_{38} = -5.3$, $p < 0.001$). The control treatment remained relatively unchanged ($t_{43} = 0.54$, $p = 0.59$; Figure 4B). Reflex impairment scores were significantly associated with final status and therefore a good predictor of fate ($\chi^2_{163,2} = 25.5$, $p < 0.001$).

Mortality and injury scores

Control fish had the lowest mortality levels (7%; $n = 27$) and no relevant injuries. Northern Pike in the CO treatment had the highest total mortality in 48 h (56%; $n = 25$; $p < 0.001$ compared with control), followed by MO (23%; $n = 26$, $p = 0.134$), MJ (19%; $n = 26$; $p = 0.250$), and CJ (15%; $n = 27$; $p = 0.669$) (Figure 5; Table 2). Fish with stringer placement through the operculum had higher mortality rates than fish with stringers through the lower jaw, regardless of cord or metal material ($\chi^2_{52,1} = 6.592$, $p = 0.010$; Table 2).

The highest probability of mortality was within the first 8 h for the CO (48%), MJ (15%), and MO (19%) treatments. Conversely, the CJ treatment had the same probability of mortality for 0–8 h and 8–24 h (7%), and the control had continuing 4% mortality for 8–24 h and 24–48 h. Rate of mortality was significantly different among groups, with a cord through the operculum having the most rapid deaths after being on the stringer and the tank control having the least ($\chi^2_{52,4} = 21.5$, $p < 0.001$; Figure 6).

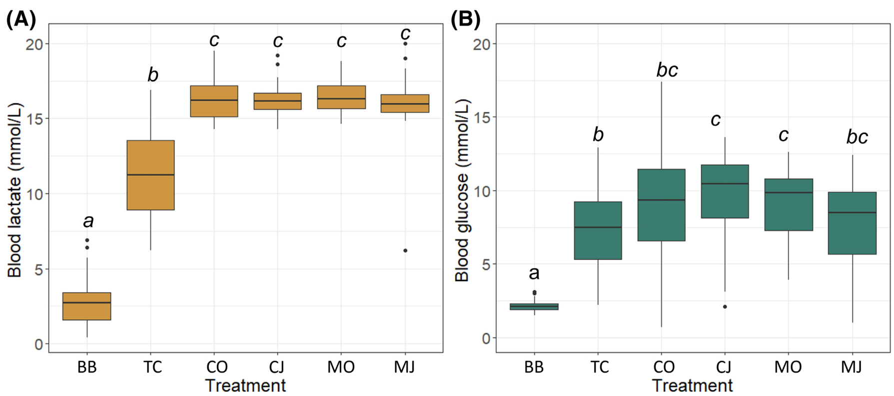

FIGURE 3 Box plots of (A) blood lactate and (B) blood glucose readings. Readings were taken from angled Northern Pike in June 2022 immediately after treatment, while fish in the baseline-blood group were sampled immediately after angling. Treatment codes are as follows: baseline blood = BB, tank control = TC, cord–operculum stringer = CO, cord–jaw stringer = CJ, metal–operculum stringer = MO, and metal–jaw stringer = MJ. The horizontal line in each box indicates the median, the box dimensions represent the 25th to 75th percentile ranges, whiskers show the 10th to 90th percentile ranges, and dots show outliers. Different letters above the boxes represent dissimilarities between treatments.

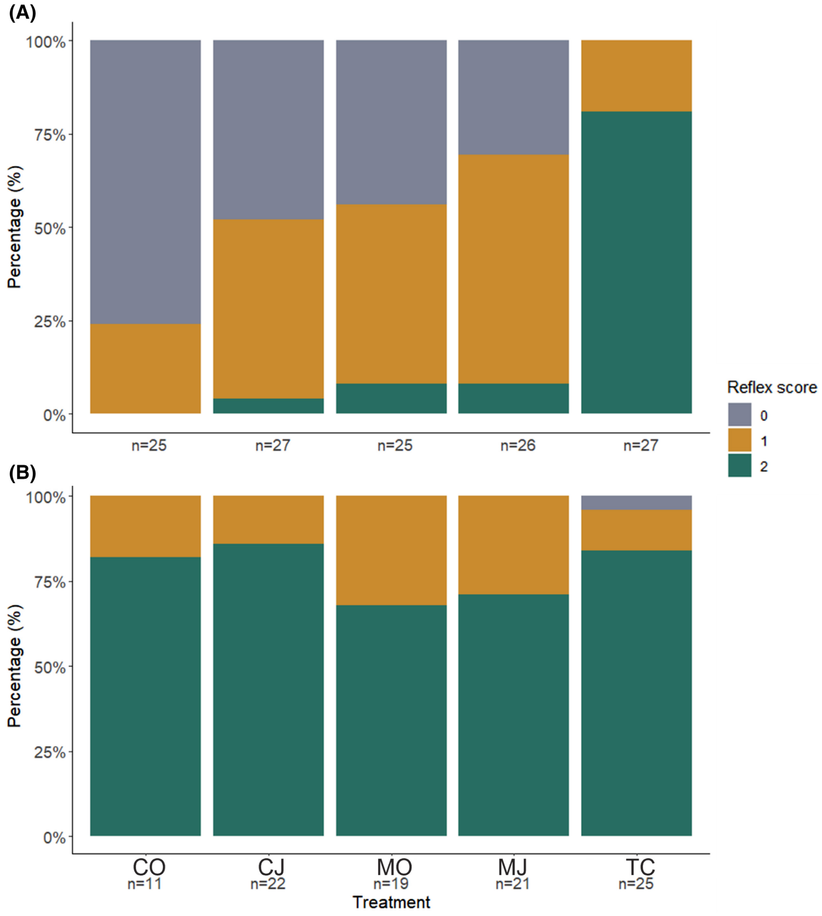

FIGURE 4 Reflex impairment scores. Northern Pike, angled from Lake Opinicon in June 2022, were given a reflex impairment score of 0, 1, or 2 (out of 2) (A) immediately after treatment and (B) 48 h after treatment, given the fish had survived this time. A score of 0 indicates full impairment, while a score of 2 indicates no impairment. Treatment codes are as follows: tank control = TC, cord–operculum stringer = CO, cord–jaw stringer = CJ, metal–operculum stringer = MO, and metal–jaw stringer = MJ.

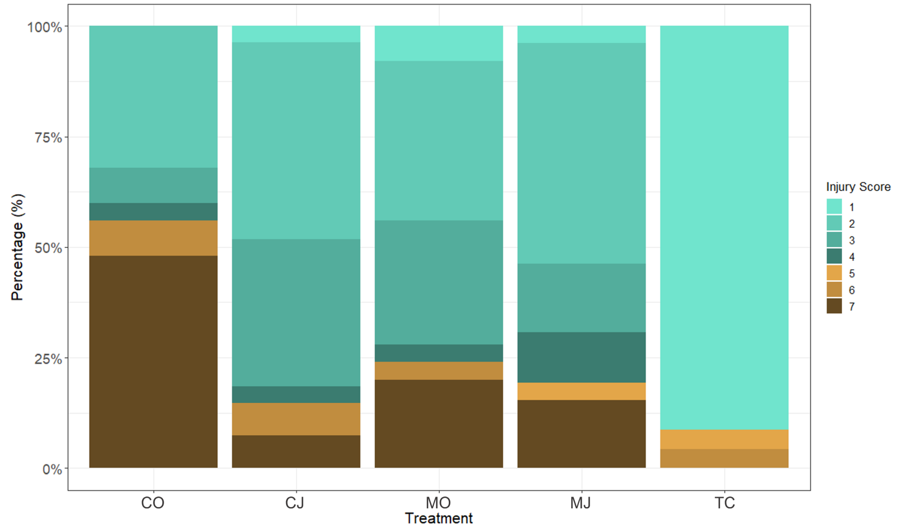

FIGURE 5 Percentage of each injury score per treatment over the 48-h posttreatment period. Orange–brown injury scores denote Northern Pike that survived 48 h, while green–blue denotes individuals that did not. An injury score of 7 represents fish that died within 8 h, injury score 6 is fish that died between 8 and 24 h, and injury score 5 is fish that died between 24 and 48 h. Explanations of all scores can be found in Table 1. See Figure 4 for treatment codes.

TABLE 2 Proportion of mortality of each treatment and time that they occurred. Treatment was administered to angled Northern Pike from Lake Opinicon in June 2022, with treatment codes as follows: tank control = TC, cord–operculum stringer = CO, cord–jaw stringer = CJ, metal–operculum stringer = MO, and metal–jaw stringer = MJ.

Treatment	*n*	Total dead	Dead <8 h	Dead 8–24 h	Dead 24–48 h
TC	27	2 (7%)		1 (3%)	1 (3%)
CO	25	14 (56%)	12 (48%)	2 (8%)	
CJ	27	4 (15%)	2 (7%)	2 (7%)	
MO	26	6 (23%)	5 (19%)	1 (4%)	
MJ	26	5 (19%)	4 (15%)		1 (4%)
All stringers	104	29 (28%)	23 (22%)	5 (5%)	1 (1%)
All operculum	51	20 (39%)	17 (33%)	3 (6%)	
All lower jaw	53	9 (17%)	6 (11%)	2 (4%)	1 (2%)
All metal	52	11 (21%)	9 (17%)	1 (2%)	1 (2%)
All cord	52	18 (35%)	14 (27%)	4 (8%)	

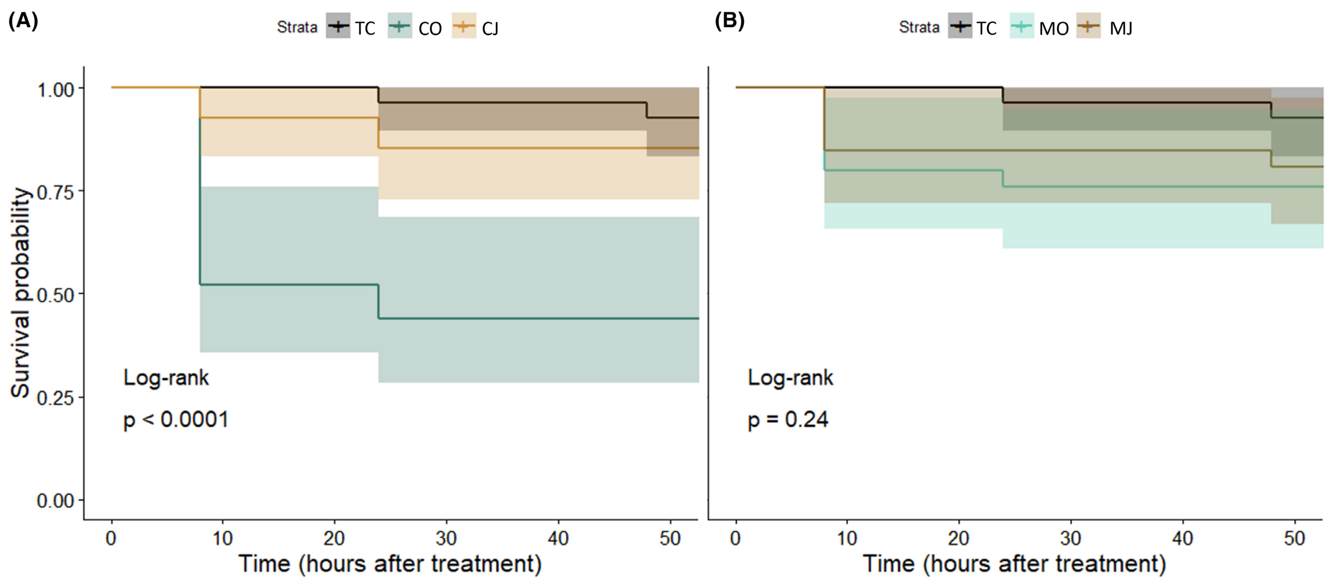

FIGURE 6 Kaplan–Meier survival curve of Northern Pike at three time intervals (8, 24, and 48 h) after treatment, showing (A) cord stringers (CO, CJ) survival over time compared with the control (TC) and (B) metal stringers (MO, MJ) survival over time compared with the control (TC). See Figure 4 for treatment codes.

The highest-ranking model from the AIC_c model selection had both treatment and average temperature as predictor variables (AIC_c = 109.1, weight = 0.60; Table 3). The conditional and marginal coefficient of determination for this model was R^2 = 0.268, with all variables statistically significant (Table 4). No other models were within a ΔAIC_c of 2.

In addition to injury scores, injuries from stringers were qualitatively described for each surviving fish immediately and after the 48-h holding period. During both assessment periods, common injuries among metal stringer treatments included small upper or lower jaw lacerations. Fish with stringers through the operculum typically had extreme lower jaw swelling and bruising (Figure 2B), visibly pale gills, lesions on the operculum, and abrasion to gill filaments. Among treatments located in the lower jaw, the only visible injuries were the puncture wounds where the stringer was fixed through the lower mouth floor. In all cases, this hole expanded to much larger than the initial puncture with skin loss around the area.

DISCUSSION

While catch-and-release best practices are well studied (Brownscombe et al. 2017), comparatively little research has been done on catch-hold-release scenarios. With high grading and selective harvest resulting in fish being culled

TABLE 3 Akaike information criterion (AIC) model selection. There were eight generalized linear mixed models with binomial distribution family with predictor variables of treatment, size of angled Northern Pike (total length), location of stringer (operculum or lower jaw), material of stringer (cord or metal), and number of motor starts during treatment and a null model. All models have stringer pair as a random effect. Abbreviations are as follows: K = number of parameters in the model and LL = log-likelihood.

Model	*K*	AIC_c	Delta AIC_c	AIC_c weight	Cumulative weight	LL
Treatment + temperature	6	109.12	0.00	0.60	0.60	−48.10
Treatment	5	112.26	3.14	0.13	0.73	−50.80
Treatment + size	6	112.53	3.41	0.11	0.84	−49.80
Treatment + motor starts	6	112.55	3.43	0.11	0.94	−49.81
Stringer location	3	114.65	5.53	0.04	0.98	−54.20
Treatment × size	9	117.03	7.90	0.01	0.99	−48.48
Stringer material	3	119.26	10.13	0.00	1.00	−56.50
Null	2	119.59	10.46	0.00	1.00	−57.73

TABLE 4 Output of the best model (see Table 3) as ranked by the AIC_c model selection. Model was a generalized linear mixed effect model with binomial distribution and included Northern Pike status (dead or alive) as a response variable, with treatment and average temperature as predictor variables and stringer pair as a random effect. Treatment codes are as follows: cord–operculum stringer = CO, cord–jaw stringer = CJ, metal–operculum stringer = MO, and metal–jaw stringer = MJ.

Variable	Estimate	SE	*Z*-value	Pr(>|*z*|)
Intercept	13.23	6.11	2.16	0.030
CJ	2.81	0.81	3.44	<0.001
MO	1.70	0.66	2.57	0.001
MJ	2.26	0.72	3.12	0.002
Average temperature	−0.627	0.28	−2.23	0.254

from retention gear, it is prudent to investigate the lethal and sublethal effects of retention gear on released fish. We found that culling Northern Pike from stringers results in higher blood lactate concentrations, reflex impairment, and moderate postrelease mortality compared with a tank control. Additionally, it is clear that cord stringers attached through the operculum are the most lethal. This study adds to the growing literature on effects of culling and retention gear on angled fish.

Blood physiology and reflex impairment

Blood physiology (Sopinka et al. 2016) and reflex impairment (Davis 2007) serve as useful ways to determine the extent of stress, health, and response to environmental changes in fish. As secondary stress responses, elevated blood glucose and lactate concentrations indicate a higher physiological disturbance (Sopinka et al. 2016). Previous studies reporting blood lactate concentrations from angled Northern Pike found ~7 mmol/L after air exposure (Arlinghaus et al. 2009), ~15 mmol/L after exercise and angling and handling (Schwalme and Mackay 1985a, 1985b), and up to 12 mmol/L after simulated catch and release (Pullen et al. 2017). The mean lactate concentration from fish on stringers in this study (16.2 mmol/L) exceeded those reported of solely angled or exhaustively exercised fish, with readings up to 20 mmol/L. In fact, of all studies measuring blood lactate in Northern Pike, we are not aware of any reported levels as high as recorded in this study. To that end, 90% of the 10 fish with lactate >18 mmol/L died in our study. This is a testament to the extent of stress experienced by fish during the 2 h on the stringer, though fish could potentially be held on stringers for much longer periods of time during typical angling and culling events. Comparatively, our control fish had an average blood lactate reading of ~12 mmol/L—similar to what Pullen et al. (2017) found after simulated catch and release. Therefore, it is probable that most of the high lactate readings in control fish were due to the angling event itself and not much influenced by the live-well retention. Our blood lactate data suggest that retention on stringers, even for just 2 h, is akin to severe exercise or hypoxia. This is not surprising given that while on the stringer, fish struggled against each other and may have had impaired respiration due to the presence of stringers in the buccal cavity and, for some fish, around the operculum.

While all stringer-treated fish had significantly lower reflex scores immediately after treatment compared with the tank control, reflex scores of surviving fish improved after 48 h. This recovery shows that any lasting effects or injury from the treatments that may have occurred were not severe enough to continue to affect the reflexes of the surviving fish. Comparatively, the control fish remained consistent with high scores both immediately after treatment and at the end of the study. Though there will always be some stress induced by any type of retention, this result along with the blood lactate readings show that sublethal effects of being held in an aerated tank or live well are negligible—but stringer-treated fish are highly affected.

Injuries and mortality

Injuries occurring from retention can have lasting impacts on released fish; while severe injuries can result in delayed mortality, smaller sublethal injuries can affect swimming behavior and growth (Cooke and Schramm 2007). Different injuries were observed for differently located treatments. Among lower-jaw-located treatments, the only visible injuries were the expanded puncture wounds, probably due to the fish pulling against the drifting boat or the fish thrashing against the stringer, in either case tearing the tissue in the lower jaw. Research on the use of lip grippers on other game fish (Bonefish *Albula vulpes* and Barramundi *Lates calcarifer*) found that they cause lower jaw holes similar to what was observed with the jaw-located treatments in this study, though both studies reported low or no mortality (Danylchuk et al. 2008; Gould and Grace 2009). As our treatment time in this study was much longer than in the previously mentioned research (2 h on a stringer versus 20–30 s of lip gripping), and assuming that the injuries were indeed comparable, the mortality witnessed from the lower-jaw-stringer treatments were probably mostly stress induced and not solely from their jaw injuries. Similarly, a study of hooking mortality found that Largemouth Bass hooked in nonlethal areas had a 98% survival rate (Wilde and Pope 2008), showing that small injuries to nonlethal areas—such as the jaw-located stringer in this study—are not likely fatal. Though we witnessed some scale abrasions from rubbing against the side of the pen (possibly due to gill and skin irritation from stringers; Fontenot and Neiffer 2004), there was no obvious sign of injury occurring in the holding pen from other fish.

Northern Pike with the stringer placed through their operculum (i.e., the CO and MO treatments) had extreme bruising and swelling immediately and 48 h after being on a stringer. It is typical in teleost fish for inflammatory responses such as what we observed to last up to 5 days, which could impact the affected fish (Fontenot and Neiffer 2004). Consistent with Cooke and Hogle's (2000) study with Smallmouth Bass, we found that among differently located treatments, stringers through the operculum had higher mortality than treatments through the lower jaw. As gills are a major organ system in fish responsible for gas exchange (Ferguson and Tufts 1992), they are much more susceptible to short-term fatal injury than minor damage to the lower jaw. As such, operculum-specific injuries from stringers, such as visibly pale gills, lesions on the operculum, and abrasion to gill filaments, likely contributed to their higher mortality. Further, the high abrasiveness of the cord stringer probably explains why the CO treatment was the most fatal (56% mortality), as it had more surface area to irritate the gills compared with the smooth metal. Like Cooke and Hogle (2000), we found that temperature indeed influences mortality of fish placed on stringers, with higher temperatures resulting in more fish deaths. As countless studies have found handling and angling at high water temperatures to have a negative effect on the well-being of fish (Gale et al. 2013), the fact that temperature was a relevant factor here is unsurprising.

Management implications

Though the order of most to least damaging of the four stringer treatments found in this study was different than Cooke and Hogle's (2000), the overall conclusion of the damage caused by stringers compared with controls remains the same. Stringer treatments in general were responsible for a mortality rate four times higher than the control treatment (CO was eight times more). Even with the high mortality rates from stringers recorded in this study, it is possible that more fish died after the 48 h from fungal infections resulting from their injuries (as in Cooke et al. 1998). We found that reflex impairment and physiological stress in addition to mortality will be significantly higher when using stringers and minimized when using live wells, assuming fish are provided with adequate water quality. Our study reveals that when fish are culled from stringers, especially in warm temperatures, the real impact on the population is much higher than the allotted harvest with the typical catch-and-release mortality rate. Fisheries managers should use clear language in regulations describing any fish placed on a stringer as part of a harvest limit and thus prohibit anglers from releasing such fish. At a minimum, culling from stringers should be disallowed when temperatures are elevated.

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CONFLICT OF INTEREST STATEMENT

There is no conflict of interest declared in this article.

DATA AVAILABILITY STATEMENT

Data will be made available upon reasonable request.

ETHICS STATEMENT

The Ontario Ministry of Natural Resources and Forestry provided scientific collection permits (1100502) and the Carleton University Animal Care Committee provided animal care approvals (CU Cooke C&R Umbrella 2022) for this study.

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