Fisheries Research 243 (2021) 106056

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Influence of artificial lure hook type on hooking characteristics, handling, and injury of angled freshwater gamefish

Alexandria Trahan [a,*], Auston D. Chhor [a], Luc LaRochelle [a], Andy J. Danylchuk [b], Steven J. Cooke [a]

[a] *Fish Ecology and Conservation Physiology Laboratory, Department of Biology and Institute of Environmental and Interdisciplinary Science, Carleton University, Ottawa, ON, K1S 5B6, Canada*
[b] *Department of Environmental Conservation, University of Massachusetts Amherst, 160 Holdsworth Way, Amherst, MA 01003-9485, USA*

A R T I C L E I N F O

Handled by: Niels Madsen

Keywords:
Recreational angling
Catch-and-release
Hooking
Injury

A B S T R A C T

Catch-and-release is practiced in recreational fisheries under the premise that released fish will survive with negligible injury and stress. However, hooking injuries may prevent that outcome from being realized. One way to potentially minimize injuries and maximize survival in angled fish is to replace treble hooks on hard plastic lures with single hooks, but the effectiveness of this tactic has yet to be tested. Our study investigated if replacing treble hooks with single hooks on hard plastic lures reduced injuries and handling for angled Northern Pike (*Esox lucius*), Smallmouth Bass (*Micropterus dolomieu*) and Largemouth Bass (*Micropterus salmoides*). Furthermore, we compared fish handling (i.e., need for use of hook removal gear) and injuries between fish that were captured with barbed and barbless hooks. Fish were angled using three types of conventional hard plastic lures (i.e., crankbaits, jerkbaits, and lipless crankbaits). Upon landing, total length of the fish, an array of hooking characteristics (i.e., number of hook points in the fish, anatomical hooking location(s)), and reflex impairment were recorded. Analyses revealed that using barbless J hooks on all lures yielded the shortest unhooking times for all species. For Smallmouth Bass caught on both crank and jerk baits, J hooks tended to result in more shallow hooking than treble hooks. Barbless treble hooks were more likely to be embedded in a sensitive location (e.g., foul hooked, gullet, gills, and/or eyes) compared to barbless J hooks in Smallmouth Bass. No other significant differences in hook types and anatomical locations were found for other species. Hook type and lure type did not influence reflex impairment or survival for any of the species. Using J hooks, especially barbless ones, on lures that traditionally have treble hooks should be considered when encouraging best angling practices for the freshwater gamefish studied here to expedite release, although the extent to which this influences mortality remains unclear.

1. Introduction

Recreational fishing is a popular activity around the globe. Although some fish are harvested, it is increasingly common that fish are released to comply with regulations or as a voluntary action linked to a conservation ethos (Arlinghaus et al., 2007). An assumption that underpins catch-and-release (C&R) as a conservation and management strategy is that mortality is low and that any injuries or sublethal disturbances are short lived (Wydoski, 1977; Cooke and Schramm, 2007). However, a growing body of research reveals that not all fish survive angling events (Muoneke and Childress, 1994; Bartholomew and Bohnsack, 2005; Arlinghaus et al., 2007). Mortality rates are highly variable and context dependent, (Bartholomew and Bohnsack, 2005; Brownscombe et al., 2017), varying widely depending on environmental factors, angler behaviour, gear type used, and species-specific responses to stress (reviewed in Brownscombe et al., 2017).

Across C&R studies, a common factor has been identified as being the single largest determinant of fish survival - anatomical hooking location, whereby fish hooked in vital areas (e.g., the gullet and/or gills) tend to experience higher mortality and bleeding compared to fish hooked in the jaw (e.g., Pelzman, 1978; Taylor and White, 1992; reviewed in Bartholomew and Bohnsack, 2005). Hooking location can be influenced by a variety of factors including lure/bait type, gear type, and angler experience (Muoneke and Childress, 1994). For example, organic baits

* Corresponding author.
E-mail address: atrahan9@gmail.com (A. Trahan).

https://doi.org/10.1016/j.fishres.2021.106056
Received 30 March 2021; Received in revised form 6 June 2021; Accepted 22 June 2021
Available online 9 July 2021

tend to result in deeper hooking locations than artificial baits while smaller baits tend to result in deeper hooking locations than larger baits (Arlinghaus et al., 2008; Fobert et al., 2009). Novice anglers are also more likely to deeply hook fish in comparison to more experienced anglers (Dunmall et al., 2001).

Hook type and hook number have also been shown to influence physical damage in recreationally angled fish (Muoneke and Childress, 1994; Brownscombe et al., 2017). For instance, circle hooks tend to yield shallower hooking locations compared to J hooks (Cooke and Suski, 2004). Many studies on salmonids have found that using single hooks on lures results in decreased mortality compared to the use of treble hooks (Hunsaker et al., 1970; Matlock et al., 1993; Nuhfer and Alexander, 1992; Warner, 1979). Similar findings have been found with Northern Pike (*Esox lucius*), where using a single hook on lures instead of a treble hook tended to result in less mortality (Burkholder, 1992). A recent study has suggested that using lures with fewer hooks and/or single hooks may help to reduce unhooking time and minimize air exposure in Largemouth Bass (*Micropterus salmoides*; Clarke et al., 2020). However, that study failed to systematically vary hook type and the presence of barbs on the same lure types. Single hooks have been shown to cause less injury and lower mortality in comparison to treble hooks in some contexts (Muoneke and Childress, 1994; Bartholomew and Bohnsack, 2005). However, there has been very little work done evaluating the effects of using a single hook on hard plastic fishing lures commonly used by anglers when targeting freshwater gamefish (Cooke and Suski, 2005). Hook type and number can also influence handling time and need to use different hook removal gear (e.g., pliers rather than bare hands), which is another factor to consider when assessing impacts on recreationally angled fish (Brownscombe et al., 2017).

Traditionally, most artificial hard body lures use treble hooks, but this tradition has been slowly changing in the angling community. There are discussions in online forums as well as increasing number of fishing media stories about the merits of replacing treble hooks on hard bodied lures with single J style hooks (e.g., Landesfeind, 2018; Waters, 2019). Northern Pike, Smallmouth Bass (*Micropterus dolomieu*), and Largemouth Bass are species that are traditionally caught with treble hooks when using hard plastic lures. As such, investigating the impacts of using single J hooks could provide insight on whether there is merit in replacing treble hooks on lures. The use of barbless hooks has also become a common practice (sometimes voluntary or mandated) in some jurisdictions as some studies suggest barbless hooks reduce injury during catch and release angling events (Meka, 2004; Bartholomew and Bohnsack, 2005). Yet, beyond salmonids (see Schill and Scarpella, 1997), there is relatively little known about the extent to which barbless hooks benefit fish caught on lures.

The primary objective of this study was to investigate if replacing treble hooks on lures with single hooks influenced hooking location, injuries and fish handling (i.e., use of different hook removal gear) and the extent to which these outcomes are moderated by barbs. To do so, we focused on hard plastic lures (i.e., crankbaits, jerkbaits, and lipless crankbaits) which are commonly used to target freshwater gamefish, and for which barbed treble hooks are the default hook type at time of purchase. This study compared treble hooks (barbed and barbless) as well as J hooks (barbed and barbless) on the different lure types. Three species were included in the study (Northern Pike, Smallmouth Bass, and Largemouth Bass) representing some of the most popular freshwater gamefish in North America. Given interspecific variation in anatomy and hook performance we did not quantitatively compare outcomes among different species.

2. Methods

2.1. Animal welfare

All experiments were conducted in accordance with regulations and guidelines set by the Canadian Council on Animal Care (Carleton University protocol AUP #110,558). Fish were collected under Scientific Collection Permit #08,577 from the Ontario Ministry of Natural Resources and Forestry.

2.2. Study site and fish capture

Angling was conducted on Lake Opinicon (44.5590 °N, 76.3280 °W), Constance Lake (45.4090 °N, 75.9797 °W), Mississippi Lake (45.0321 °N, 76.2029 °W), Big Rideau Lake (44.7706 °N, 76.2152 °W), and the Rideau River (45.3151 °N, 75.6971 °W) from May to August in both 2019 and 2020. These bodies of water were chosen because they support popular sport fisheries where Largemouth Bass, Smallmouth Bass, and Northern Pike are targeted with lures. Water temperature varied from 10.5–29 °C over the course of the study. All lakes are in eastern Ontario and have similar fish communities and characteristics (i.e., they support both cool water and warmwater fish communities).

2.3. Fishing gear

To catch fish, anglers spent time casting and trolling from a boat between 05:00 to 22:00. Fish were captured by anglers of varying skill levels using crankbaits, jerkbaits, and lipless crankbaits. Crankbaits were typically trolled while the other two lure types were cast and retrieved. Crankbaits are hard plastic diving lures with a lip that were equipped with two hooks and the average size used was 6.5 ± 0.7 cm. The most-used crankbaits were Strike King KVD Squarebill, Rapala DT (Dives-To) Series and Pro Model 6XD Crankbait. Trolling of crankbaits was standardized in that we trolled with combustion motors set to the lowest forward speed which was ~ 2.5 km/hr. In rare instances where crankbaits were cast, they were retrieved at speeds intended to emulate trolling. Lipless crankbaits are also hard plastic diving lures but do not have a lip and vibrate in the water. These lures were fished by casting and reeling in at a steady speed (not unlike the speed at which the crankbaits were trolled). Because these lures were fished over weeds, the retrieval speed was rather consistent among anglers (i.e., just fast enough to keep the lures above the weeds). They were equipped with two hooks and the average size used was 7.0 ± 0.9 cm and were mostly Rapala Rippin' Raps and Cotton Cordell Super Spot. Jerkbaits are slender shallow lures retrieved with a jerking motion done by the angler such that they elicit a variable retrieve speed whereby the lures alternated between being still and being rapidly pulled through the water. They were equipped with two hooks and the average size used was 10 cm, mostly Rapala X-Raps (Fig. 1). The study used treble hooks that came on the lures (barbed and barbless) as well as J hooks (7237 - Light

Fig. 1. Image of two jerkbaits used in the study with A) barbless treble hooks and B) barbed single J hooks.

Inline Single VMC). Single J hooks were either size 1/0 or 2/0 depending on the size of the lures (smaller lures had smaller hooks, and vice versa). To convert barbed hooks to barbless, the barb on each hook was pinched using pliers. Fish were caught on medium to medium-heavy spinning and baitcasting (2–2.1 m) rods with gear matched to the size of the lure and the target species paired with braided line (minimum 9 kg braid). Although anglers were of different skill levels, these lures were all fished actively and simply require holding a rod (trolling) or reeling in. This is unlike working soft plastic lures or live/organic bait where bites may not be evident for the angler and where angler expertise can thus influence outcomes for fish (see Gutowsky et al., 2017; Clarke et al., 2020).

2.4. Hook removal

Fish were landed as quickly as possible (< 1 min) and netted when they were near the side of the boat. The fish were immediately transferred to a padded water-filled trough where hook removal was conducted while the fish was submerged. Hook removal was conducted by an experienced angler (at least 2 years of angling experience) and was defined as the length of time between the angler touching the hook to when the hook was removed from the fish. The anatomical location (upper lip, lower lip, corner, etc.), number of embedded hooks, and depth of each hook point was recorded. Hooking depth was converted into a proportion in relation to total length to account for size differences among fish (Cooke et al., 2001; Gutowsky et al., 2017). When fish had more than one embedded hook point, the average of the hooking depth (in proportion to total length) was used for analysis. The type of lure and hook(s) that fish were caught on was also recorded. Hook removal was classified as "self", where the hook came out of the fish without any help from an angler, "hand", where anglers used their hands to remove hook, and 'tool', where the angler used pliers or haemostats to remove hooks. Pliers were typically used for larger fish while hemostats were the tool of choice for smaller fish. Before release, total length of the fish was measured to the nearest mm and recorded.

2.5. Reflexes and survival

We recorded three key reflex action mortality predictors (RAMP) to evaluate if the fish was impaired following our treatments (Davis, 2007; Raby et al., 2015): 1) ability to maintain equilibrium, 2) reaction to a tail grab (burst swimming), and 3) vestibular ocular response (i.e. eye tracking). The reflexes were scored as present or absent. Overall, only six Northern Pike in our entire experiment were euthanized due to low RAMP score and inability to recovery and subsequently swim away. All other fish were released immediately following the evaluation.

2.6. Data analysis

R Version 1.1.447 (R Core Team, 2019) was used to conduct statistical analyses. Number of hooks, unhooking time, sensitive location, mean hook depth, depth of deepest hook, hook removal method, and reflexes/survival were compared among treatments using linear regression models. We ensured assumptions were met by analyzing plots of standardized residuals vs. theoretical quartiles (Q-Q), residuals vs. fitted values, square root of standardized residuals vs. fitted values (scale-location) and examined outliers by calculating Cook's distance. Significant effects were assessed using Type 2 sum of squares. The least square means function (lsmeans) function from the emmeans package was used to assess post hoc differences along with false discovery rate (FDR) corrections (Lenth, 2016; 2020). Statistical significance was accepted at $\alpha = 0.05$ and, unless otherwise noted, all values were presented as means ± SEM.

3. Results

A total of 572 fish were captured and included in our study, including 220 Northern Pike, 103 Smallmouth Bass, and 246 Largemouth Bass (Table 1), from across the five different study lakes (Lake Opinicon n = 380, Constance Lake n = 53, Mississippi Lake n = 67, the Rideau River n = 12, Big Rideau Lake n = 60).

3.1. Number of hook points

The number of hook points in fish varied from 1 to 5 (of a maximum of 6 hook points on lures with two treble hooks). The number of hook points in fish did not differ by hook type or lure type for any of the species (see Supplementary Material).

3.2. Unhooking time

Unhooking time ranged from 0 to 305 s (mean = 10 ± 29 s). There was no difference in hook removal times among lures (Northern Pike, $F_2 = 2.74$, $p = 0.067$; Smallmouth Bass, $F_1 = 0.92$, $p = 0.34$ and Largemouth Bass, $F_2 = 2.69$, $p = 0.07$). Hook type had a significant effect on the unhooking time for all three species (Northern Pike, $F_3 = 9.30$, $p < 0.001$; Smallmouth Bass, $F_3 = 5.46$, $p = 0.002$ and Largemouth Bass, $F_3 = 11.32$, $p < 0.001$) (Fig. 2). Across species, barbed treble hooks took the longest to remove while barbless single hooks were the quickest to remove (see Supplementary Material). For Northern Pike caught with crankbaits, lipless crankbaits, and jerkbaits, single barbless hooks had the fastest unhooking time and barbed treble had the slowest. For Smallmouth Bass caught with crankbaits and jerkbaits, single barbless hooks had the fastest unhooking time and treble barbed hooks had the slowest. For Largemouth Bass caught with crankbaits, lipless crankbaits and jerkbaits, single barbless hooks had the fastest unhooking time and treble barbed had the slowest.

3.3. Use of hook removal gear

There was a significant association between hook type and hook removal method for Northern Pike, Smallmouth Bass, and Largemouth Bass (Northern Pike, $LR_2 = 43.32$, $p < 0.001$; Smallmouth Bass, $LR_2 = 19.05$, $p < 0.001$ and Largemouth Bass, $LR_2 = 62.79$, $p < 0.001$), although no post-hoc differences were observed. Differences in hook type did not influence the use of different hook removal gear, although pliers were used more frequently than bare hands to remove barbed treble hooks from Northern Pike (Z Ratio = -6.464, $p < 0.001$).

3.4. Anatomical hooking location

Hooking location was not influenced by lure types for any species. For Smallmouth Bass, there was an overall significant difference in the distribution of hook placement among the different hook types ($LR_3 = 10.3$, $p = 0.016$), but there were not any differences observed using a post-hoc test.

3.5. Hooking depth

The average hook depth (measured from snout to tail) ranged from 1 to 235 mm (mean 36 ± 26 mm, median = 31 mm). Once hooking depths were corrected to body length (as per Cooke et al., 2001), there were no significant differences in average relative hooking depth between lure or hook type in Northern Pike. Average hooking depth was significantly influenced by hook type in Smallmouth Bass and Largemouth Bass ($LR_3 = 12.76$, $p = 0.005$). For Smallmouth Bass, crankbait and jerkbait single barbless hooks were shallower than treble barbed and barbless lures. Overall, there was a significant difference of average hooking depth in hook type in Largemouth Bass ($LR_3 = 12.57$, $p = 0.006$), however, there were no pairwise differences of average hook depth between hook types observed.

Table 1
Size distribution and total number of fish caught for every combinator of lure and hook per species.

Species	Lure	Hook Type	Total (n)	Min TL (mm)	Max TL (mm)	Avg TL (mm)	SE +/- (mm)
Northern Pike	Crank Bait	J Barbless	11	400	800	626	132
		J Barbed	14	440	885	614	134
		Treble Barbed	29	465	647	559	53
		Treble Barbless	11	438	840	608	134
	Jerk Bait	J Barbless	14	445	855	565	120
		J Barbed	13	460	746	561	91
		Treble Barbed	23	257	785	532	122
		Treble Barbless	22	403	690	511	71
	Lipless Crank Bait	J Barbless	11	535	875	691	109
		J Barbed	13	409	779	552	112
		Treble Barbed	27	345	640	501	63
		Treble Barbless	32	320	735	515	86
Smallmouth Bass	Crank Bait	J Barbless	10	178	402	303	114
		J Barbed	12	169	389	275	64
		Treble Barbed	13	170	390	287	79
		Treble Barbless	10	175	444	289	92
	Jerk Bait	J Barbless	13	140	335	274	53
		J Barbed	19	250	430	335	55
		Treble Barbed	13	185	395	315	67
		Treble Barbless	13	195	420	292	68
Largemouth Bass	Crank Bait	J Barbless	17	189	446	317	68
		J Barbed	12	210	385	332	46
		Treble Barbed	33	215	380	299	45
		Treble Barbless	14	175	430	299	76
	Jerk Bait	J Barbless	11	100	500	345	112
		J Barbed	20	265	425	333	48
		Treble Barbed	11	224	365	303	47
		Treble Barbless	48	229	583	328	57
	Lipless Crank Bait	J Barbless	12	220	527	338	91
		J Barbed	11	218	411	316	54
		Treble Barbed	24	160	486	310	64
		Treble Barbless	33	235	425	330	41

3.6. Deepest hook

The deepest hook distance ranged from 1 to 235 mm (mean 39 ± 28 mm). There were no significant differences of deepest hook depth between lure or hook type in Northern Pike. Hook type had a significant effect on the deepest hooking location in Smallmouth Bass ($LR_3 = 7.1$, $p < 0.001$). The deepest hooks were barbless treble hooks followed respectively by barbed treble, barbless single, and barbed single, with barbed single being the most shallow hook (Fig. 3). Hook type had an overall significant effect on the deepest hooking depth in Largemouth Bass ($F_3 = 3.29$, $p = 0.021$). There were no significant differences found in the post-hoc test.

3.7. Reflexes and immediate mortality

There was no significant effect of lure type on RAMP score detected for any species. Overall, there was a significant effect of hook type on RAMP score ($F_3 = 4.001$, $p = 0.008$) for Northern Pike, where treble barbed hooks were more likely to have a negative impact on reflexes followed by treble barbless then J barbed hooks. Six Northern Pike were euthanized due to low RAMP score (two fish caught with jerkbaits that had barbed treble hooks, two fish caught with lipless crankbaits that had barbless treble hooks and one fish for both jerkbait single barbless and lipless crankbait treble barbed). In all instances, substantial bleeding was observed, and fish failed to swim away. No other fish were euthanized during the study implying that they were in good condition at time of release and were thus not subject to immediate hooking mortality.

4. Discussion

Overall findings from our study demonstrate that replacing treble hooks with single hooks on hard plastic lures reduces deep hooking and unhooking time for Northern Pike, Smallmouth Bass, and Largemouth Bass. Across species, we found limited evidence or added benefit (increased survival) of using barbless hooks; the use of single hooks over treble hooks derived the greatest benefit. However, that benefit was still rather minor and did not translate to differences in immediate mortality (which were negligible). Nonetheless, with barbed treble hooks being the most common and commercially available hook type on freshwater hard bodied plastic lures, and anecdotal evidence from social media showing that some anglers are replacing their treble hooks with single J hooks, the results of our study validate how changing hook types can minimize hooking injury and dehooking times which may increase the welfare status of angled fish.

Terminal gear selection influences the number of hook points that can penetrate a fish (Muoneke and Childress, 1994). A treble hook is composed of three single hooks attached to a common shaft, which increases the potential of more hook points piercing a fish during angling events compared to a single hook. Decreasing the number of hooks on lures is thought to reduce injuries (Muoneke and Childress, 1994). However, we did not find any significant differences in the number of hook points that pierced fish between treble and single hooks, or between lure types and hook types across all species observed in this study. This extended to no differences in bleeding or reflex impairment (i.e., equilibrium, burst swimming and/or vestibular ocular response). Given that individual fish will attack a lure in different ways given context, it is not entirely surprising that the number of hooks in a fish was similar across lure types and hook types. Aside from a study by Gutowsky et al. (2017), we know very little about how fish interact with baits and how this varies among individual anglers and fish.

We found that using single barbless hooks on hard plastic baits expedited unhooking time for Northern Pike, Smallmouth Bass, and Largemouth Bass (Fig. 1) In comparison to other studies (e.g., Arlinghaus et al., 2008; Clarke et al., 2020), we did not find any significant relationship between lure types and unhooking time for any of the species. Unhooking time is an important indicator of handling time and

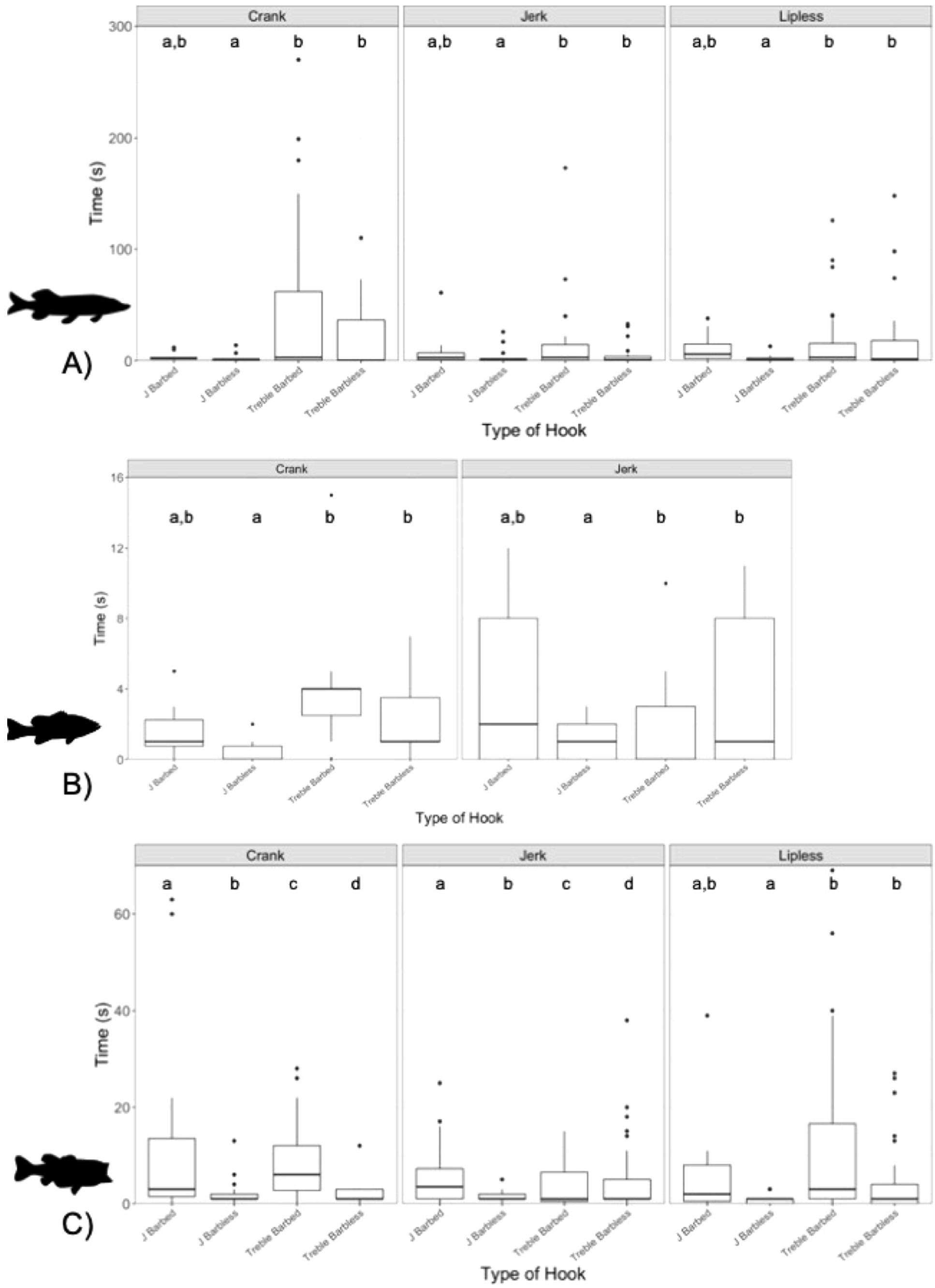

Fig. 2. Time to remove various hook types (J Barbed, J Barbless, Treble Barbed and Treble Barbless) for: A) Northern Pike (Crank Bait n = 65, Jerk Bait n = 72, and Lipless Crank Bait n = 83); B) Smallmouth Bass (Crank Bait n = 45, and Jerk Bait n = 58); and C) Largemouth Bass (Crank Bait n = 76, Jerk Bait n = 90, and Lipless Crank Bait n = 80).

air exposure that fish experience during angling events (Cook et al., 2015). Although Northern Pike, Smallmouth Bass, and Largemouth Bass are somewhat resilient to air exposure, effects on behaviour and physiology have been documented (e.g., Cooke et al., 2002; Thompson et al., 2008; White et al., 2008; Arlinghaus et al., 2009) and may impact long-term fitness (Davis, 2002; Coggins et al., 2007). In general, it is highly recommended that air exposure is minimized to decrease physiological (Pankhurst and Dedualj, 1994; Cook et al., 2015; Gagne et al., 2017) and behavioural disturbances (Thorstad et al., 2004; Klefoth et al., 2008; Arlinghaus et al., 2009). Since Smallmouth Bass and Largemouth Bass teeth cause minimal damage to anglers, the majority of the hooks were removed by hand. Northern Pike have multiple rows of sharp teeth which resulted in pliers being used more often to avoid angler injury. Barbed treble hooks had the longest unhooking time in Northern Pike, and the use of pliers to remove the hooks was more common. The large number of possible penetrating barbed hook points on the lures and the number of sharp teeth in Northern Pike increased the difficulty of removing hooks, compared to hook removal of Smallmouth Bass and Largemouth Bass. Although it is thought that removal of hooks with pliers is more efficient (Clarke et al., 2020; but see Cooke et al., 2021), our study showed that using pliers was associated with significantly longer unhooking times compared to removing hooks by hand. This is confounded by the fact that easy-to-remove hooks did not require pliers. It is clear that tool intervention was required to remove hooks when in difficult (deep) anatomical locations, accounting for longer unhooking times.

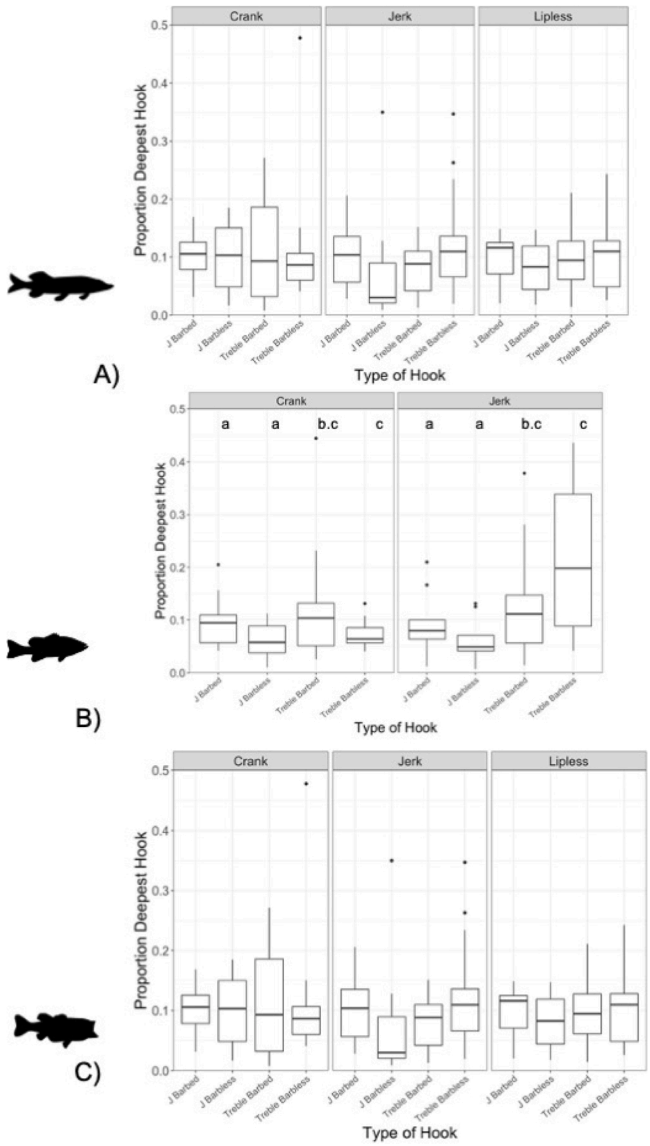

Fig. 3. The deepest hook of various hook types (J Barbed, J Barbless, Treble Barbed and Treble Barbless) for: A) Northern Pike (Crank Bait n = 65, Jerk Bait n = 72, and Lipless Crank Bait n = 83); B) Smallmouth Bass (Crank Bait n = 45, and Jerk Bait n = 58); and C) Largemouth Bass (Crank Bait n = 76, Jerk Bait n = 90, and Lipless Crank Bait n = 80) in proportion to total length of fish.

Lure type did not have a significant impact on the hooking location in any of the species, which is in contrast from previous studies (e.g., Myers and Poarch, 2000; Arlinghaus et al., 2008; Clarke et al., 2020). In other species like Chinook Salmon, anatomical hooking location was shown to be a key factor in predicting fish survival (Linsay et al., 2004). Salmon that were hooked in the gills, gullet, eyes, and tongue had higher mortality rates that fish hooked in less critical locations (Lindsay et al., 2004). Hooking in vital areas, such as the gills and gullet, can cause increased bleeding and reduced survival of fish captured by recreational angling (Muoneke and Childress, 1994; Lyle et al., 2007; Arlinghaus et al., 2008; Clarke et al., 2020). For our study, hooking in sensitive locations was only influenced by hook type in Smallmouth Bass, which could be related to how this species attacks the bait.

Hooking depth was significantly related to hook type in Smallmouth Bass and Largemouth Bass. Previously, it was found that treble hooks are deeply ingested less often compared to single hooks (Muoneke and Childress, 1994). However, our findings for Smallmouth Bass and Largemouth Bass contradict this. There was a significant increase in average hooking depth in Smallmouth Bass when treble hooks (barbed and barbless) were used vs barbless single hooks. Yet, hooking depth does not necessarily translate into hooks in the gullet or gills and in the case of hard plastic baits is often in the context of external (foul) hooking. For Largemouth Bass, there was a significant increase in average hooking depth when barbless treble hooks were used compared to barbed treble hooks, as well as barbed treble hooks vs barbed single hooks. Similarly, the deepest hooking location in Smallmouth Bass was significantly different between hook types. Hooking depth ranged from shallow to deep as follows; single barbless hooks, single barbed hooks, barbless treble hooks, and treble barbed hooks (Fig. 3). Treble hooks cause more damage once they are embedded into fish (Muoneke and Childress, 1994) including Largemouth Bass (Clarke et al., 2020). Therefore, this contradictory finding supports the use of single hooks to minimize internal hooking damage and minimize average hooking depth in Smallmouth Bass and Largemouth Bass. Hooking depth is a key factor in determining injury intensities (Arlinghaus et al., 2007). When hooks are embedded deep in fish, they are harder to remove resulting in higher likelihood of injury, air exposure, and mortality (Arlinghaus et al., 2007; Bartholomew and Bohnsack, 2005; Cooke and Suski, 2005; Cooke et al., 2012).

Overall immediate mortality was minimal, due to the lack of major hooking injuries. When instances of mortality did occur, they were due to fish being hooked in sensitive locations and/or long unhooking time. Hook removal is usually accompanied with air exposure, however all hook removals in our study were done while fish were submerged. Although we standardized this in our study, removing hooks while fish are submerged in water is unlikely to occur when fish are landed by regular anglers. RAMP was assessed before fish were released and there were few cases where fish experienced loss of equilibrium or other reflex impairment. Fish were not monitored post-release; thus, long-term effects are unknown. Wound severity or amount of bleeding were not taken into account in this study. However, previous studies have found that wound severity and bleeding were often greater when single hooks were used versus treble hooks (Muoneke, 1992; Nuhfer and Alexander, 1992). Yet, treble

hooks may cause less mortality than single hooks because they are more difficult to swallow (Klein, 1965; Muoneke, 1992).

Fish were caught across two years in multiple seasons; therefore, water temperature was not consistent (10.5–29 °C), and the added effects of water temperature were not considered in this study. The effects of water temperature have been well studied, demonstrating increased stress and mortality in fish at higher water temperatures (Cooke and Suski, 2005; Arlinghaus et al., 2007; Hühn and Arlinghaus, 2011). However, with so little mortality observed here it is not possible to assess such relationships. Our study did not account for fight time which could have impacted injuries and RAMP scores. Also, for future studies, other lure types should be considered (i.e., top water lures, spybaits etc.), as well as other hook type combinations (i.e., circle hooks, octopus hooks, etc.). Additionally, although fishing with barbless hooks can decrease handling time (Meka, 2004), it can also negatively influence catch rate (Alós et al., 2008). As such, future studies should consider investigating hooking to capture ratio for each hook type (barbed vs barbless) to see if a specific hook type increases success rates of capture.

5. Conclusion

Our research provides evidence that hook type on hard plastic lures used to capture Northern Pike, Smallmouth Bass, and Largemouth Bass is important for determining some welfare outcomes. Lure and hook type influenced the unhooking time, hooking location, average hook depth, and deepest hook in most cases. Specifically, barbed treble hooks typically took longer to remove compared to single barbless hooks. Angler education programs, fishing guides, and fishing media should promote scientifically tested species-specific best practices to potentially reduce population-level effects. This study provides a direct comparison of various lure and hook combinations and builds scientific knowledge on the benefits that come with replacing treble hooks with single hooks (also observed in Clarke et al., 2020), expediting unhooking time, and minimizing air exposure. Substituting treble hooks for single J hooks on hard plastic lures decreases unhooking time which can reduce injuries in Northern Pike, Smallmouth Bass, and Largemouth Bass. The ability to easily remove hooks can decrease air exposure (assuming most anglers do not remove hooks in water as we did here) creating better welfare outcomes for angled fish. Hook removal tools such as pliers and haemostats are beneficial to use when hooks are in difficult to remove locations and to promote angler safety, particularly for fish with sharp dentition such as Northern Pike. In conclusion, single barbless hooks on lures reduce hooking time compared to treble barbed hooks in Northern Pike, Smallmouth Bass, and Largemouth Bass. Anglers should consider their use when targeting these species. Future studies should investigate the long-term survival post-release for each possible combination of lure and hook type as well as investigate other factors that may promote long-term survival of fish post C&R events.

CRediT authorship contribution statement

Alexandria Trahan: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Resources, Writing - original draft, Visualization. **Auston D. Chhor:** Software, Formal analysis, Investigation, Resources, Writing - review & editing. **Luc LaRochelle:** Investigation, Resources, Writing - review & editing. **Andy J. Danylchuk:** Writing - review & editing, Supervision. **Steven J. Cooke:** Conceptualization, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgements

We extend our gratitude to Queen's University Biological Station for serving as a base for this research. Brooke Etherington, Jon Kubelka, Adam Williamson, Alice Abrams, Daniel Glassman and Connor Reid assisted with data collection. We thank Jacob Brownscombe for assistance with data analyst. We are grateful to two anonymous referees for input on our manuscript. Funding was provided by the Anderson Family Foundation with additional support from the Natural Sciences and Engineering Research Council of Canada and the Canada Research Chairs Program. All research was conducted in accordance with the guidelines of the Canadian Council on Animal Care as administered by Carleton University (Protocol 110558).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.fishres.2021.106056.

References

Alós, J., Palmer, M., Grau, A.M., Deudero, S., 2008. Effects of hook size and barbless hooks on hooking injury, catch per unit effort, and fish size in a mixed-species recreational fishery in the western Mediterranean Sea. Ices J. Mar. Sci. 65 (6), 899–905. https://doi.org/10.1093/icesjms/fsn067.

Arlinghaus, R., Cooke, S.J., Lyman, J., Policansky, D., Schwab, A., Suski, C., et al., 2007. Understanding the complexity of catch-and-Release in recreational fishing: an integrative synthesis of global knowledge from historical, ethical, social, and biological perspectives. Rev. Fish. Sci. 15 (1–2), 75–167. https://doi.org/10.1080/10641260601149432.

Arlinghaus, R., Klefoth, T., Kobler, A., Cooke, S.J., 2008. Size selectivity, injury, handling time, and determinants of initial hooking mortality in recreational angling for northern pike: the influence of type and size of bait. N. Am. J. Fish. Manag. 28, 123–134. https://doi.org/10.1577/M06-263.1.

Arlinghaus, R., Klefoth, T., Cooke, S.J., Gingerich, A., Suski, C., 2009. Physiological and behavioural consequences of catch-and-release angling on northern pike (Esox lucius). Fish. Res. 97, 223–233. https://doi.org/10.1016/j.fishres.2009.02.005.

Bartholomew, A., Bohnsack, J.A., 2005. A review of catch-and-release angling mortality with implications for no-take reserves. Rev. Fish Biol. Fish. 15, 129–154. https://doi.org/10.1007/s11160-005-2175-1.

Brownscombe, J.W., Danylchuk, A.J., Chapman, J.M., Gutowsky, L.F.G., Cooke, S.J., 2017. Best practices for catch-and-release recreational fisheries – angling tools and tactics. Fish. Res. 186, 693–705. https://doi.org/10.1016/j.fishres.2016.04.018.

Burkholder, A., 1992. Mortality of Northern Pike Captured and Released With Sport Fishing Gear. Alaska Department of Fish and Game, Division of Sport Fish, Anchorage, p. 92.

Clarke, S.H., Brownscombe, J.W., Nowell, L., Zolderdo, A.J., Danylchuk, A.J., Cooke, S. J., 2020. Do angler experience and fishing lure characteristics influence welfare outcomes for largemouth bass? Fish. Res. 233 (September 2020), 105756. https://doi.org/10.1016/j.fishres.2020.105756.

Coggins, L.G., Catalano, M.J., Allen, M.S., Pine, W.E., Walters, C.J., 2007. Effects of cryptic mortality and the hidden costs of using length limits in fishery management. Fish Fish. 8 (3), 196–210. https://doi.org/10.1111/j.1467-2679.2007.00247.x.

Cook, K.V., Lennox, R.J., Hinch, S.G., Cooke, S.J., 2015. FISH Out of WATER: How Much Air is Too Much? Fisheries 40 (9), 452–461. https://doi.org/10.1080/03632415.2015.1074570.

Cooke, S.J., Schramm, H.L., 2007. Catch-and-release science and its application to conservation and management of recreational fisheries. Fish. Manag. Ecol. 14 (2), 73–79. https://doi.org/10.1111/j.1365-2400.2007.00527.x.

Cooke, S.J., Suski, C.D., 2004. Are circle hooks an effective tool for conserving marine and freshwater recreational catch-and-release fisheries? Aquat. Conserv. Mar. Freshw. Ecosyst. https://doi.org/10.1002/aqc.614.

Cooke, S.J., Suski, C.D., 2005. Do we need species-specific guidelines for catch-and-release recreational angling to effectively conserve diverse fishery resources? Biodivers. Conserv. 14 (5), 1195–1209. https://doi.org/10.1007/s10531-004-7845-0.

Cooke, S.J., Philipp, D.P., Dunmall, K.M., Schreer, J.F., 2001. The influence of terminal tackle on injury, handling time, and cardiac disturbance of rock bass. N. Am. J. Fish. Manag. 21 (2), 333–342 https://doi.org/10.1577/1548-8675(2001)021<0333:tiotto>2.0.co;2.

Cooke, S.J., Schreer, J.F., Wahl, D.H., Philipp, D.P., 2002. Physiological impacts of catch-and-release angling practices on largemouth bass and smallmouth bass. Am. Fish. Soc. Symp. 31, 489–512.

Cooke, S.J., Nguyen, V.M., Murchie, K.J., Danylchuk, A.J., Suski, C.D., 2012. Scientific and stakeholder perspectives on the use of circle hooks in recreational fisheries. Bull. Mar. Sci. 88 (3), 395–410. https://doi.org/10.5343/bms.2011.1056.

Cooke, S.J., Cooke, C.J., Cooke, J.T., Cooke, B.W., Danylchuk, A.J., Brownscombe, J.W., 2021. Efficacy of dehooking tools for the removal of hooks from the jaw region of angled fish. Fish. Res. 240, 105965.

Davis, M.W., 2002. Key Principles for Understanding Fish Bycatch Discard Mortality. https://doi.org/10.1139/F02-139.

Davis, M.W., 2007. Simulated fishing experiments for predicting delayed mortality rates using reflex impairment in restrained fish. Ices J. Mar. Sci. 64 (8), 1535–1542. https://doi.org/10.1093/icesjms/fsm087.

Dunmall, K.M., Cooke, S.J., Schreer, J.F., McKinley, R.S., 2001. The effect of scented lures on the hooking injury and mortality of smallmouth bass caught by novice and experienced anglers. N. Am. J. Fish. Manag. 21 (1), 242–248. https://doi.org/10.1577/1548-8675(2001)021<0242:TEOSLO>2.0.CO;2.

Fobert, E., Meining, P., Colotelo, A., O'connor, C., Cooke, S.J., 2009. Cut the line or remove the hook? An evaluation of sublethal and lethal endpoints for deeply hooked bluegill. Fish. Res. 99, 38–46. https://doi.org/10.1016/j.fishres.2009.04.006.

Gagne, T.O., Ovitz, K.L., Griffin, L.P., Brownscombe, J.W., Cooke, S.J., Danylchuk, A.J., 2017. Evaluating the consequences of catch-and-release recreational angling on golden dorado (Salminus brasiliensis) in Salta, Argentina. Fish. Res. 186, 625–633. https://doi.org/10.1016/j.fishres.2016.07.012.

Gutowsky, L.F.G., Sullivan, B.G., Wilson, A.D.M., Cooke, S.J., 2017. Synergistic and interactive effects of angler behaviour, gear type, and fish behaviour on hooking depth in passively angled fish. Fish. Res. 186, 612–618. https://doi.org/10.1016/j.fishres.2016.05.026.

Hühn, D., Arlinghaus, R., 2011. Determinants of hooking mortality in freshwater recreational fisheries: a quantitative meta-analysis. Angler Environ. Soc. Econ. Biol. Ethic. Dimens. 75 (April 2014), 141–170.

Hunsaker, D., Marnell, L.F., Sharpe, F.P., 1970. Hooking mortality of yellowstone cutthroat trout. Progress. Fish-Cult. https://doi.org/10.1577/1548-8640(1970)32[231:HMOYCT]2.0.CO;2.

Klefoth, T., Kobler, A., Arlinghaus, R., 2008. The impact of catch-and-release angling on short-term behaviour and habitat choice of northern pike (Esox lucius L.). Hydrobiologia 601 (1), 99–110. https://doi.org/10.1007/s10750-007-9257-0.

Klein, W.D., 1965. Mortality of Rainbow Trout caught on single and treble hooks and released. Prog. Fish Cult. 27, 171–172.

Landesfeind, E., 2018. VMC Inline Single Hooks Can Upgrade Your Lures. Retrieved February 8, 2021, from. https://www.bdoutdoors.com/vmc-inline-single-hooks/.

Lenth, Russell V., 2016. Least-squares means: the r package lsmeans. J. Stat. Softw. 69 (1), 1–33. https://doi.org/10.18637/jss.v069.i01.

Lenth, R.V., 2020. Emmeans: Estimated Marginal Means, Aka Least-squares Means. R package version 1.5.1. https://CRAN.R-project.org/package=emmeans.

Lindsay, R.B., Schroeder, R.K., Kenaston, K.R., Toman, R.N., Buckman, M.A., 2004. Hooking mortality by anatomical location and its use in estimating mortality of spring chinook salmon caught and released in a river sport fishery. N. Am. J. Fish. Manag. 24 (2), 367–378. https://doi.org/10.1577/m02-101.1.

Lyle, J.M., Moltschaniwskyj, N.A., Morton, A.J., Brown, I.W., Mayer, D., 2007. Effects of hooking damage and hook type on post-release survival of sand flathead (Platycephalus bassensis). Mar. Freshw. Res. 58 (5), 445–453. https://doi.org/10.1071/MF06233.

Matlock, G.C., Mceachron, L.W., Dailey, J.A., Unger, P.A., Chai, P., 1993. Management briefs: short-term hooking mortalities of red drums and spotted seatrout caught on single-barb and treble hooks. N. Am. J. Fish. Manag. 13 (1), 186–189. https://doi.org/10.1577/1548-8675(1993)013<0186:MBSTHM>2.3.CO;2.

Meka, J.M., 2004. The influence of hook type, angler experience, and fish size on injury rates and the duration of capture in an alaskan catch-and-Release rainbow trout fishery. N. Am. J. Fish. Manag. 24 (4), 1309–1321. https://doi.org/10.1577/m03-108.1.

Muoneke, M.I., 1992. Hooking mortality of white crappie, Pomoxis annularis Rafinesque, and spotted bass, Micropterus punctulatus (rafinesque), in Texas reservoirs. Aquacult. Fish. Manage. 23, 87–93.

Muoneke, M.I., Childress, W.M., 1994. Hooking mortality: a review for recreational fisheries. Rev. Fish. Sci. 2 (2), 123–156.

Myers, R.A., Poarch, S.M., 2000. Effects of bait type and hooking location on post-release mortality of largemouth bass. Proceedings of the Annual Conference of the Southeastern Association of Fish and Wildlife Agencies 39–45.

Nuhfer, A.J., Alexander, G.R., 1992. Hooking mortality of trophy-sized wild brook trout caught on artificial lures. N. Am. J. Fish. Manag. 12 (3), 634–644. https://doi.org/10.1577/1548-8675(1992)012<0634:hmotsw>2.3.co;2.

Pankhurst, N.W., Dedualj, M., 1994. Effects of capture and recovery on plasma levels of cortisol, lactate and gonadal steroids in a natural population of rainbow trout. J. Fish Biol. 45 (6), 1013–1025. https://doi.org/10.1111/j.1095-8649.1994.tb01069.x.

Pelzman, R.J., 1978. Hooking mortality of juvenile largemouth bass Micropterus salmoides. Calif. Fish Game 64, 185–188.

R Core Team, 2019. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Raby, G.D., Hinch, S.G., Patterson, D.A., Hills, J.A., Thompson, L.A., Cooke, S.J., 2015. Mechanisms to explain purse seine bycatch mortality of coho salmon. Ecol. Appl. 25 (7), 1757–1775. https://doi.org/10.1890/14-0798.1.

Schill, D.J., Scarpella, R.L., 1997. Barbed hook restrictions in catch-and-release trout fisheries: a social issue. N. Am. J. Fish. Manag. 17 (4), 873–881.

Taylor, M.J., White, K.R., 1992. A meta-analysis of hooking mortality of nonanadromous trout. N. Am. J. Fish. Manag. 12 (4), 760–767. https://doi.org/10.1577/1548-8675(1992)012<0760:AMAOHM>2.3.CO;2.

Thompson, L.A., Cooke, S.J., Donaldson, M.R., Hanson, K.C., Gingerich, A., Klefoth, T., Arlinghaus, R., 2008. Physiology, behavior, and survival of angled and air-exposed largemouth bass. N. Am. J. Fish. Manag. 28 (4), 1059–1068.

Thorstad, E.B., Hay, C.J., Næsje, T.F., Chanda, B., Økland, F., 2004. Effects of catch-and-release angling on large cichlids in the subtropical Zambezi River. Fish. Res. 69 (1), 141–144. https://doi.org/10.1016/j.fishres.2004.04.005.

Warner, K., 1979. Mortality of landlocked Atlantic Salmon hooked on four types of fishing gear at the hatchery. Progress. Fish-Cult. 41 (2), 99–102. https://doi.org/10.1577/1548-8659(1979)41[99:MOLASH]2.0.CO;2.

Waters, S., 2019. Switch Multiple Hooks for Singles to Improve Catch-and-Release. Retrieved February 8, 2021, from. https://www.sportfishingmag.com/switch-multiple-hooks-for-singles-to-improve-catch-and-release/.

White, A.J., Schreer, J.F., Cooke, S.J., 2008. Behavioral and physiological responses of the congeneric largemouth (Micropterus salmoides) and smallmouth bass (M. dolomieu) to various exercise and air exposure durations. Fish. Res. 89 (1), 9–16.

Wydoski, R.S., 1977. Relation of hooking mortality and sublethal hooking stress to quality fishery management. In: Barnhart, R.A., Roelofs, T.D. (Eds.), Catch and Release Fishing: A Decade of Experience. Humboldt State University, Arcata, CA, pp. 43–87.