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MANAGEMENT BRIEF

Corrosion Rates and Compression Strength of White Sturgeon-Sized Fishing Hooks Exposed to Simulated Stomach Conditions

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Abstract
Field reports indicate that many White Sturgeon *Acipenser transmontanus* ingest hooks internally, but the length of time required for hooks to corrode, facilitating passage through their digestive system, is not well understood. Using a buffered acidic solution to simulate stomach conditions, a laboratory experiment was used to estimate the speed at which sturgeon-sized hooks (2.0-mm wire diameter) lost weight and compression strength and to evaluate whether loss of hook weight and compression strength was affected by hook abrasion, such as may occur when baited hooks are bounced along the bottom of the river or when ingested hooks are ground between hard food items in the gizzard of a sturgeon. After 399 d, hooks lost an estimated 34% of their weight and 70% of their compression strength. Abrading the hooks with stones before and throughout the study accelerated weight loss by 34% (after 399 d) compared with nonabraded hooks but did not accelerate the loss of compression strength. Abrasion increased the variability between hooks in weight loss but not in compression strength. Regardless of hook abrasion, the compression strength of some hooks was reduced essentially to 0 N within 1 year of constant exposure to stomach-like acidic conditions.

Throughout human history, vastly different materials have been used to hook and catch fish, from simple wooden, bone, or stone "hooks" to highly engineered metals with specialized protective coatings (Edappazham 2010). Modern commercial and recreational anglers can choose hooks in a wide range of sizes and colors that are strong, thin, and corrosion-resistant. Most modern hooks are constructed from high carbon steel wire and protected by metallic or lacquer finishes to prevent the steel core from corroding, though some hooks are still constructed from metals that are naturally resistant to corrosion, including stainless steel or brass (Edappazham 2010).

While corrosion-resistant hooks last longer in an angler's tackle box, they also resist corrosion inside a fish. Fish ingest angling hooks in a variety of ways. First, anglers sometimes hook a fish too deeply to safely remove the hook, so they cut the line and leave the hook lodged in the fish under the assumption that the fish will eventually dislodge the hook or the hook will dislodge itself as it oxidizes over time (e.g., Schill 1996; Tsuboi et al. 2006; Fobert et al. 2009). Second, if an angler hooks a fish in the mouth but the line breaks during fighting, the fish may inadvertently consume the hook (rather than expelling it) when it dislodges at a later time. Finally, a fish (particularly benthic-feeding fish) may inadvertently consume a hook still attached to bait on the bottom of the river, such as when an angler snags up and breaks his line. In the Hell's Canyon reach of the Snake River in Idaho, an estimated 15% of White Sturgeon *Acipenser transmontanus* have angling tackle in their digestive system (Idaho Power Company 2015), and the presence of such metal has been documented in many other sections of the Snake and Columbia rivers (Idaho Power Company 2015; Halvorson et al. 2018). However, deep hooking while fishing with bait for this benthic-feeding fish appears to be extremely rare (i.e., 0.5%: Lamansky et al. 2018). This discrepancy suggests that deep hooking is not the primary mechanism by which White Sturgeon ingest fishing tackle into their digestive system. Rather, sturgeon are more

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likely swallowing hooks that have broken off either in their mouth during the angling bout or have been found on the river bottom. The river bottom explanation is further supported by X-ray images of metal inside White Sturgeon, much of which consists of terminal tackle not targeting (and rarely if ever hooking) sturgeon, such as bait hooks and jigs for salmon, trout, bass, and catfish (Lamansky and Daw 2015; Bowersox et al. 2016).

Besides vital organ damage and subsequent mortality directly related to deep hooking while angling (Mason and Hunt 1967; Schill 1996) or potentially at a later point in time as ingested hooks shift inside the fish (Broadhurst et al. 2007), other potential negative consequences to hook consumption are that ingested tackle might obstruct food consumption, digestion, and assimilation, or lead to internal lesions, peritonitis, and infection (Borucinska et al. 2002). Indeed, deeply hooked fish occasionally can experience reduced growth rates (e.g., Jenkins 2003; Aalbers et al. 2004). Whether such indirect negative impacts materialize may be influenced by how long it takes for ingested angling hooks to corrode and pass through the digestive system of fish, which is also not well understood.

Most existing studies reporting the length of time hooks persist inside fish have been of short duration and a secondary objective of the study (e.g., Mason and Hunt 1967; Marnell 1969; Hulbert and Engstrom-Heg 1980; Schill 1996; Butcher et al. 2007). Few published studies have formally investigated corrosion rates or the compression (or tensile) strength of hooks (Varghese et al. 1997; Edappazham et al. 2007). Studies that have reported the length of time required for hooks to corrode have often used a salt spray to measure corrosion rates (e.g., Kitano et al. 1990; Edappazham et al. 2010; McGrath et al. 2011), an approach approved by the American Society for Testing and Materials (ASTM E352-93 2000). While such a salt-spray test may evaluate general corrosion resistance as a measure of hook longevity in marine fisheries, the test likely does not accurately depict how hooks would corrode in a biologically active environment such as the digestive tract of fish. Compression strength is important in the context of hook passage by White Sturgeon because their digestive system includes a large muscular gizzard that functions to crush and grind fish bones, mussel shells, crayfish, and other hard food items they consume. While most fish that have ingested hooks must either egest them, pass them whole, or wait for them to corrode and break on their own, sturgeon gizzard action may compress hooks directly or compress other hard food items against the hooks, hastening hook corrosion and breakage.

For this study, hooks commonly used by White Sturgeon anglers were chosen to evaluate whether hooks with different finishes corrode at different rates when exposed to stomach-like acidic conditions. Some hooks were abraded to simulate conditions hooks may encounter while drifting along the bottom of a river (before hooks are consumed by sturgeon) or grinding between hard food items in the gizzard (after hooks are consumed). The objectives of the study were to (1) evaluate the speed at which hooks with various finishes lost weight and compression strength while being exposed to stomach-like acidic conditions, and (2) determine whether abrading the protective finish on hooks hastened the loss of weight or compression strength.

METHODS

Simulated stomach solution.— During digestion in a fish stomach, hydrochloric acid (HCl) is secreted along with enzymes to hydrolyze food for absorption (Bond 1979). The pH in teleost stomachs varies depending on the species of interest and the food consumed but generally ranges between 1 and 4 (Bond 1979; Smith 1980; Moyle and Cech 1988). A solution of HCl buffered with KCl was prepared to simulate the conditions inside a White Sturgeon stomach. The solution was buffered to keep the pH consistent throughout the experiment. First, 149.1 g of KCl was dissolved in 1.0 L of deionized water to make a 2-M KCl solution. Next, 324 mL of 2-M HCl was mixed with deionized water to a volume of 3.0 L. Finally, the 1.0-L KCl solution was combined with 3.0 L of HCl solution to achieve a 4.0-L, 2-M HCl–KCl stock solution. Before use, 275 mL of the stock solution was mixed with 750 mL of deionized water to achieve a 0.5-M HCl–KCl solution with a pH of 2. The pH of the solution was confirmed with a digital pH meter (Eutech Instruments pH spear).

Study design.— Angling hooks were selected in sizes and finishes commonly used for White Sturgeon angling and available in local stores. Size 5/0 Gamakatsu Octopus J hooks made of high carbon steel wire (2.0 mm diameter) with four different finishes were selected: bronze (model 02115), red lacquer (model 02315), silver nickel (model 02015), and black nickel (model 02415). A total of 50 hooks of each of the four finishes (200 hooks in total) were divided evenly into two groups: abraded and nonabraded hooks. Hooks were further divided into groups of five hooks of the same finish to place separately in beakers.

To abrade hooks, one group of five hooks were placed in a 7 × 11 × 16-cm plastic box filled approximately halfway with 40 rounded granitic stones (Mohs hardness = 5.5–6.5) ranging from 1 cm as the smallest to 5 cm as the largest (i.e., river gravel). The box was shaken three times to simulate the abrasion hooks might receive as described above. Nonabraded hooks did not receive this treatment.

All hooks (in groups of five) were immersed in 100 mL of the acid solution contained in Pyrex beakers for a total of 399 d. Hooks were weighed using a jeweler's scale (±0.002 mg) prior to being placed in the acid solution. Beakers were held at ambient room temperature

(18–21°C) and were sealed with Parafilm to prevent evaporation and protect against spills.

Hook weight loss measurement.— Hooks were removed approximately once each week from the acid solution, rinsed, dried, and weighed. A 1-L beaker was filled with a solution of tap water and approximately 250 g of baking soda to neutralize any acid remaining on the hooks. We removed the hooks from the acid solution with nonreactive forceps and dipped them into the baking soda solution for up to 30 s or until any visible reaction ceased. Each hook was then rinsed in tap water followed by deionized water. After rinsing, the hooks were placed on absorbent paper towels and allowed to air dry. Hooks were then individually weighed and returned to the acid solution. Hooks receiving the abrasion treatment were abraded (as noted above) each time before being returned to their respective beakers. The pH of the acid solution in each beaker was checked with a digital pH meter, and the acid solution was replaced if the pH was above 3; replacement was required frequently throughout the study.

Hook compression strength measurement.— On 21 separate occasions over the course of the study, some hooks were removed from the experiment to test for compression strength. Compression strength is the amount of force (in newtons) required to cause a material to fail or break. Hooks were treated as above up to and including the day of removal from the weight loss experiment. After neutralizing, rinsing, and air-drying the hooks, they were stored individually in labeled, sealed, Whirl-Pak plastic bags until all compression strength testing after the experiment was terminated.

Compression strength was determined using an 810 MTS Mechanical Test Frame with uniaxial test force. The compression rate was 25 μm/s, and data was recorded every 10 Hz (0.001 s). Each hook was mounted in a custom-made compression test fixture. A parallel block was used to align the bend of the hook perpendicular to the compression surfaces, where it was secured using a pinch clamp and machined V-grooves. The top platen of the compression test fixture was fixed directly in line with the center of the load cell, while the lower platen was able to translate on a parallel plane to the upper platen for proper hook alignment. The hooks were compressed to failure and the maximum force required was recorded.

Data analyses.— For hook weight loss analyses, each beaker was treated as the experimental unit, since individual hooks within each beaker could not be individually identified without tagging or marking them, thereby potentially influencing their weight loss. Using a general linear model (GLM), mean beaker hook weight (as the response variable) was related to hook finish and abrasion treatments (both discrete independent variables) and to days of the experiment (continuous independent variable). Beaker was included as a random effect in the model to account for a beaker effect. Of primary interest was whether hooks with different finishes lost weight at different rates; a day × hook finish interaction term tested for this difference. Also of interest, was whether abraded or nonabraded hooks lost weight at different rates, and a day × abrasion interaction term was included to test for this effect. Second-order interactions were not evaluated.

For compression strength analyses, each hook was treated as the experimental unit, since compression strength could only be measured once for each hook. As with hook weight loss analyses, differences in compression strength of hooks with different finishes or that were abraded or not abraded were analyzed with a GLM. Day × hook finish and day × abrasion interaction terms were used to test whether the rate of the loss of compression strength differed between hook finishes and abrasion treatments, respectively. Also of interest for the compression strength model was whether initial compression strength differed between hook finishes. Again, second-order interactions were not evaluated for the compression strength model.

For both GLM models, residuals were analyzed diagnostically to evaluate normality and equal variance assumptions. Residuals showed minimal heteroscedasticity for either model (based on residual versus predicted plots), and log transformations did not reduce heteroscedasticity. Residuals were nonnormally distributed for the hook weight loss data set (based on statistical significance of the Shapiro–Wilk test for normality), but data transformations were not made to this data set for three reasons: (1) the raw data did not graphically portray any nonlinear patterns (see Figure 1); (2) no data transformation normalized the residuals; and (3) the residual histogram and normal probability plot suggested that residuals were fundamentally distributed normally, despite the Shapiro–Wilk test results.

As a measure of variability in hook corrosion, we calculated the CV (100·SD/mean) for hook weight and compression strength for each beaker on each day of measurement. We averaged within-beaker CVs for hook weight and compression strength and plotted mean CVs through time; abraded and nonabraded hook treatments were summarized separately. All statistical analyses were conducted using SAS (SAS Institute 2009) with $\alpha = 0.05$.

RESULTS

A total of 6,683 hook weight and 212 compression strength measurements were taken during the course of the 399-d experiment. Initial individual hook weights ranged from 1.10 to 1.21 g across all finishes. Mean initial hook weight was very similar for black nickel (mean = 1.18 g, SE < 0.01), red lacquer (1.19 g, SE < 0.01), and silver nickel (1.19 g, SE < 0.01) finishes, but was slightly lower

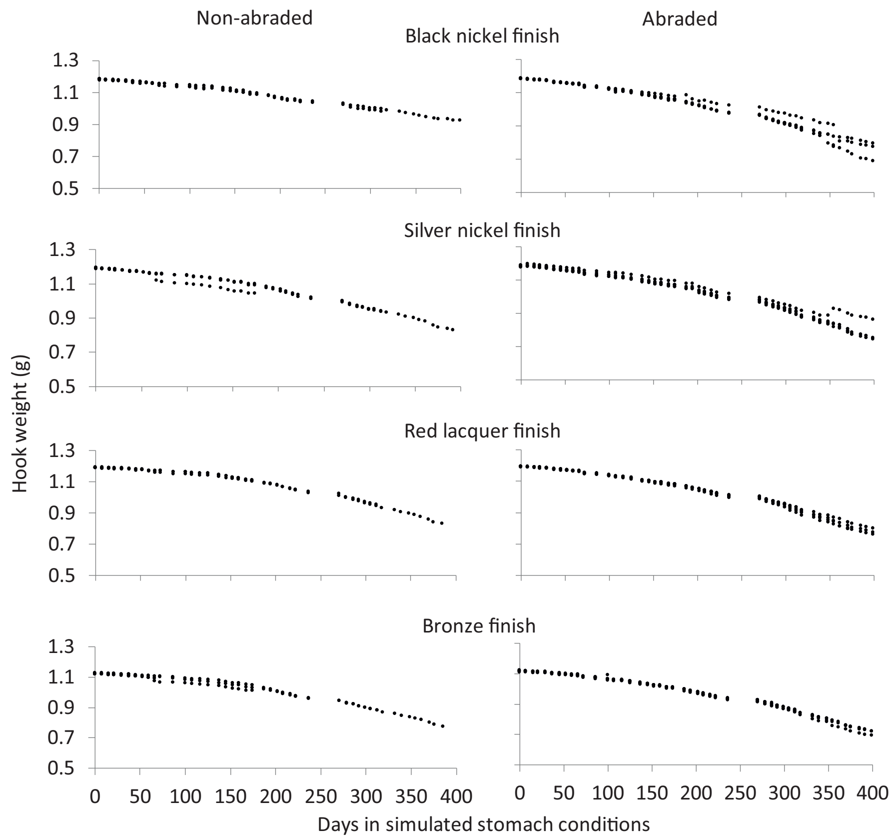

FIGURE 1. Scatterplot of mean hook weight (by beaker) over time for abraded and nonabraded sturgeon-sized fishing hooks of various finishes exposed to simulated stomach-like acidic solutions in a laboratory setting.

for hooks with a bronze finish (mean = 1.12 g, SE < 0.01).

All hooks in the simulated stomach conditions steadily corroded and lost weight over time (Figure 1). After 399 d, hooks had lost an estimated 34% of their initial weight (Table 1). There was no difference in the rate of weight loss between hook finishes (Table 1) as indicated by the nonsignificant day × finish interaction term in the weight loss GLM ($F = 0.58$, df = 3, $P = 0.63$). Hook abrasion accelerated weight loss by 34% after 399 d (Table 1), which the day × abrasion interaction term indicated was a significant rate of increase relative to nonabraded hooks ($F = 38.78$, df = 1, $P < 0.001$).

Mean initial compression strength for each hook finish before any abrasion averaged 334 N, ranging from 322 to 343 N, and did not differ between finishes (Table 2). The rate at which hooks lost compression strength through time in the simulated stomach conditions was higher than the rate of weight loss (Figure 2). After 399 d, hooks had lost an estimated 70% of their compression strength (Table 2). The rate of compression strength loss did not differ between finishes (Table 2), as indicated by the nonsignificant day × finish interaction term ($F = 0.25$, df = 3, $P = 0.86$). Abrading the hooks also did not significantly influence the rate of compression strength loss (day × abrasion interaction term: $F = 0.22$, df = 1, $P = 0.64$).

Within-beaker variation at the beginning of the experiment was low for both hook weight and compression strength, regardless of the abrasion treatment (Figure 3). However, as the hooks corroded through time, within-beaker variation in hook weight and compression strength increased steadily, especially for compression strength. Abrading the hooks increased the within-beaker variation in weight loss but not for compression strength. For abraded and nonabraded hooks combined, within-beaker CV after 399 d was, on average, over three times higher for hook compression strength (CV = 108.5) than for hook weight (CV = 33.6). For weight loss, within-beaker CV for abraded hooks (CV = 31.4) was more than twice that of nonabraded hooks (CV = 14.1).

DISCUSSION

The results of the present study indicate that the compression strength of size 5/0 Gamakatsu Octopus J hooks declined faster and was more variable after prolonged

TABLE 1. Coefficients, SEs, and test statistics from general linear models relating hook finish, hook abrasion, and time to the weight loss of sturgeon-sized fishing hooks exposed to simulated stomach-like acidic solutions in a laboratory setting.

Coefficient	Estimate	SE	*t*	*P*
Intercept	1.22360	0.00457	267.83	<0.001
Day	−0.00103	0.00005	−23.13	<0.001
Abrasion (yes)				
Abrasion (no)	−0.01435	0.00400	−3.45	<0.001
Finish: silver nickel				
Finish: black nickel	−0.01078	0.00586	−1.84	0.066
Finish: bronze	−0.06826	0.00587	−11.63	<0.001
Finish: red lacquer	0.00486	0.00587	0.83	0.408
Day × abrasion (yes)				
Day × abrasion (no)	0.00026	0.00004	6.23	<0.001
Day × finish (silver nickel)				
Day × finish (black nickel)	0.00007	0.00006	1.25	0.213
Day × finish (bronze)	0.00005	0.00006	0.90	0.369
Day × finish (red lacquer)	0.00006	0.00006	0.94	0.345

TABLE 2. Coefficients, SEs, and test statistics from general linear models relating hook finish, hook abrasion, and time to the compression strength of sturgeon-sized fishing hooks exposed to simulated stomach-like acidic solutions in a laboratory setting.

Coefficient	Estimate	SE	*t*	*P*
Intercept	334.051	36.107	9.25	<0.001
Day	−0.588	0.133	−4.41	<0.001
Abrasion (yes)				
Abrasion (no)	−0.014	0.004	−3.45	<0.001
Finish: silver nickel				
Finish: black nickel	32.314	39.593	0.82	0.415
Finish: bronze	−28.022	32.633	−0.86	0.392
Finish: red lacquer	48.416	39.280	1.23	0.219
Day × abrasion (yes)				
Day × abrasion (no)	0.055	0.117	0.47	0.639
Day × finish (silver nickel)				
Day × finish (black nickel)	0.086	0.158	0.54	0.587
Day × finish (bronze)	−0.039	0.131	−0.30	0.764
Day × finish (red lacquer)	0.020	0.156	0.13	0.900

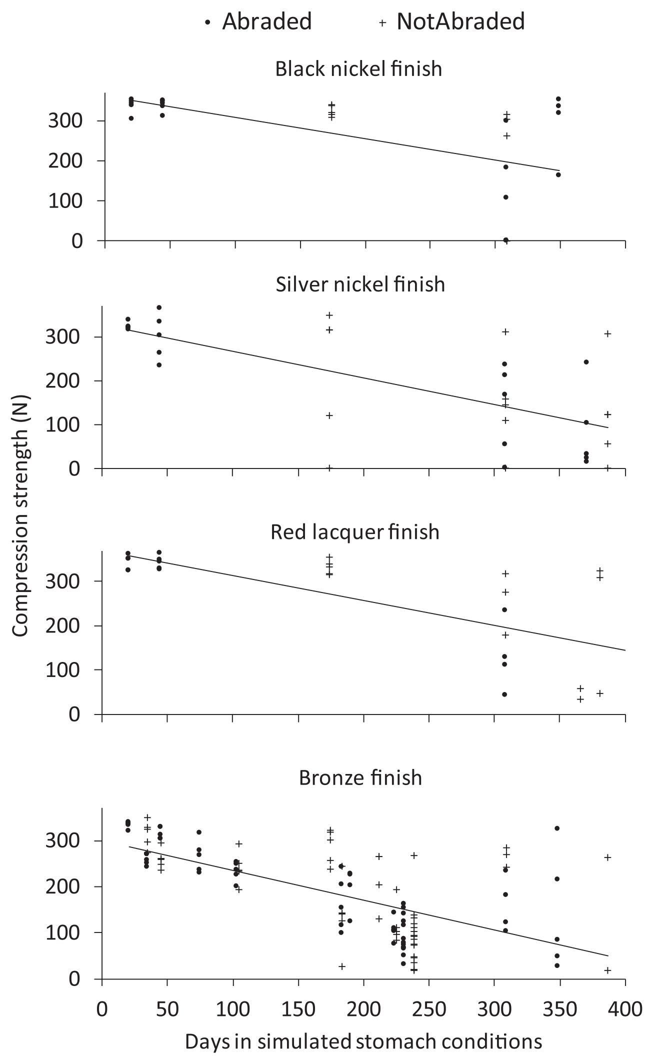

FIGURE 2. Scatterplot of the compression strength over time for individual abraded and nonabraded sturgeon-sized fishing hooks of various finishes exposed to simulated stomach-like acidic solutions in a laboratory setting. Solid lines through the data represent trend lines.

exposure to stomach-like acidic conditions than hook weight. Within the first year of our experiment, compression strength for at least some hooks of all finishes had been reduced essentially to 0 N, regardless of whether they were abraded. In contrast, only the abraded hooks lost an appreciable amount of weight, with over 80% of the abraded hooks losing at least half of their initial weight after 1 year compared to only 5% of the nonabraded hooks. While hook weight loss is a clear sign of corrosion, considering the size of the hooks used for White Sturgeon angling, they may need to break before they can be passed through the digestive system; thus, compression strength probably has more influence on hook passage time than hook weight loss. We used sturgeon-sized hooks with 2.0-mm-diameter wire in our study, but wild White Sturgeon also commonly consume other types of angling tackle, including hooks used for salmon and steelhead *Oncorhynchus mykiss*, bass and steelhead jigs, and trout hooks

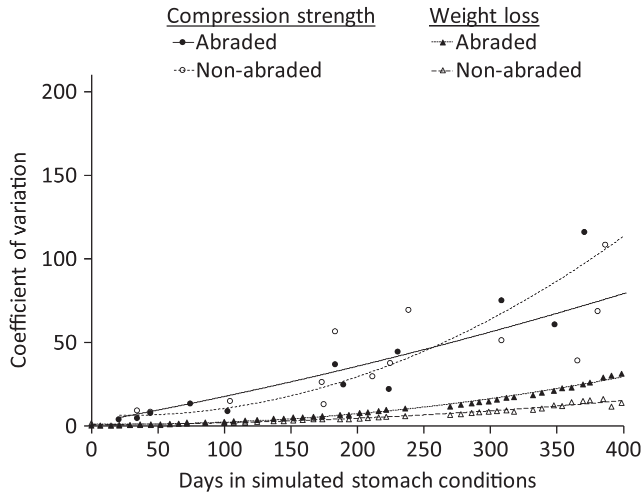

FIGURE 3. Within-beaker CVs for hook weight and compression strength over time for abraded and nonabraded sturgeon-sized fishing hooks exposed to simulated stomach-like acidic solutions in a laboratory setting. Curvilinear lines through the data represent polynomial trend lines, which fit the data better than other relationships.

(Bowersox et al. 2016). Nonsturgeon angling gear, typically made from thinner wire, should corrode even faster (and presumably pass through their digestive system quicker) than the hooks in our study.

The muscle wall of a White Sturgeon's gizzard is hypertrophic and is designed to aid in grinding up hard food items, such as fish bones or shells, for further digestion (Buddington and Christofferson 1985). Although the actual compression force a hook might experience in White Sturgeon gizzards is unknown, considering that bivalves are common in White Sturgeon diets (Muir et al. 1988; McCabe et al. 1993), their gizzard may have enough strength to bend even new fish hooks if they are in the proper orientation between other hard food items. Vasconcelos et al. (2010) found that 811 N of force were required to compress 100-mm shells of the smooth clam *Callista chione*. Male humans can exert about 100 N of force with palm pinching and about 450 N of force with hand grip strength (Mathiowetz et al. 1985). Considering the hardness of some food items that sturgeon consume, their gizzards can likely exert similar force. While such exertion of force may speed the process of hook breakage and passage, it is clearly not requisite because broken hooks have been observed in other fish species without muscular gizzards (Mason and Hunt 1967; Broadhurst et al. 2007). Nevertheless, for the size and wire diameter of hooks used in the present study, the internal compression of hooks or adjacent hard food structures may hasten hook corrosion and passage.

This study was designed to be on the severe end of sturgeon digestive environments by exposing hooks to constant pH levels of 2–3 at ambient room temperature (18–21°C). In reality, the pH of a sturgeon stomach is likely higher than 3 when food is not present, and water temperatures that White Sturgeon experience are often cooler than in our study, which could slow hook corrosion (Pauling 1970). While the pH in the lower digestive tract of White Sturgeon is likely near neutral (Smith 1980), sturgeon-sized hooks are likely obstructed from passage into the lower digestive region by the stomach sphincter until they corrode and break into pieces, making the pH of sturgeon intestines irrelevant to hook corrosion. The amount of abrasion hooks may experience from hard food items in White Sturgeon gizzards is also unknown and may be different from the abrasion our test hooks received. Therefore, the speed at which hooks lose weight and compression strength inside the digestive tract of a wild sturgeon may differ from our study.

Common advice given to anglers is that if a fish is hooked so deeply that removing the hook with fingers or pliers is difficult or impossible, the line should be cut close to the body and the fish released. Many studies suggest that, compared with forcefully removing such hooks, fish survive better when the line is cut and the fish is released without removing the hook (e.g., Schill 1996; Tsuboi et al. 2006; Fobert et al. 2009); it is assumed that the hook will corrode over time and eventually pass out of the body. For benthic feeders such as White Sturgeon that live in waters where fishing with bait for a variety of species is popular, ingested tackle may stem more from the consumption of baited gear off the river bottom than from deep hooking (Lamansky et al. 2018). Regardless of how the tackle is consumed, our results suggest that sturgeon-sized hooks will require considerable time in a sturgeon's stomach before hooks are sufficiently oxidized to break into pieces, and abrasion will likely accelerate the process.

The present study investigated the corrosion of hooks from one manufacturer made with the same wire diameter in four different finishes, and we recognize that not all hooks are made the same. While hook manufacturers are motivated to produce strong, corrosion-resistant hooks that appeal to anglers, prolonged hook resistance to corrosion may hinder the conservation of sensitive species or the sustainability of popular recreational fisheries. The lack of comparable studies highlights the importance of further research comparing the corrosion of various hooks from different manufacturers using various wire diameters and finishes to gain a better understanding of how these factors affect the passage of ingested hooks in species like White Sturgeon. How the presence of metal in the digestive tracts of White Sturgeon affects important population vital rates such as growth and survival is another avenue of research that is important to the long-term conservation of this species.

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