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[Article]

Influence of Circle Hook Size on Hooking Efficiency, Injury, and Size Selectivity of Bluegill with Comments on Circle Hook Conservation Benefits in Recreational Fisheries

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Abstract.—Hook size is an important consideration in the use of circle hooks as a conservation tool for minimizing the injury and mortality of marine fishes, but little is known about the role of hook size in the performance of hooks in recreational freshwater fisheries. In this study, we angled 100 bluegills *Lepomis macrochirus* on each of five different-sized circle hooks (1/0, 2, 6, 10, and 14). The largest hook size (1/0) had low hooking and capture efficiency but selected larger individuals. The smallest hook size also had low hooking efficiency and resulted in the selection of smaller individuals. Intermediate hook sizes captured fish of intermediate size. Jaw hooking rates generally increased with decreasing hook size, whereas roof hooking rates decreased. Gullet hooking was restricted to the three smallest hook sizes. Relative hooking depth and incidences of bleeding were uniformly low for all hook sizes. Similarly, the fish were generally easy to remove from the hook irrespective of hook size. Our mortality projections revealed no trends associated with hook size, our overall mortality rate being less than 1%. This study suggests that circle hooks function most effectively when the entire hook can fit in the mouth of the fish and when the shank-to-point distance is large enough to permit jaw hooking. Size selectivity for larger individuals can be achieved by using larger hook sizes. However, large circle hooks will also catch smaller fish that will be more likely to be hooked in injurious anatomical locations. Therefore, we recommend the use of intermediate-sized hooks for maximizing hook performance in terms of size selectivity, efficiency, and conservation.

For years, fisheries management agencies have restricted the use of different types of terminal tackle for specialty fisheries based on actual or perceived variation in the performance of the gear (Muoneke and Childress 1994). Examples of restrictions include prohibiting the use of organic and live bait (Payer et al. 1989; Schisler and Bergersen 1996), artificially scented baits (Dunmall et al. 2001), and barbed hooks (Falk et al. 1974; Cooke et al. 2001). Because the hook itself is largely responsible for the injury to the fish (Muoneke and Childress 1994), tackle manufacturers have attempted to develop and modify hooks to impart conservation benefits over conventional hook designs. The most promising development in the area of hook design is the circle hook for marine and freshwater fisheries (Cooke and Suski 2004). Circle hooks differ from conventional hooks in that the point of the hook is aligned perpendicular to the shank of the hook rather than parallel to the shank as with conventional hook types. Due to this design, circle hooks should minimize deep hooking in potentially lethal regions and instead hook fish in the edge of the mouth, upper jaw, or corner of the mouth (Montrey 1999).

In marine fisheries, circle hooks have proven to be an effective conservation tool leading to significant decreases in injury and mortality rates without reducing capture efficiency (Caruso 2000; Lukacovic 2000; Grover et al. 2002; Prince et al. 2002; Skomal et al. 2002; Cooke and Suski 2004).

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The performance of circle hooks in freshwater fisheries has been less clear, although they are being widely promoted (e.g., Stange 1999; Cooke and Suski 2004). Cooke et al. (2003c) reported that largemouth bass *Micropterus salmoides* caught using circle hooks experienced lower injury rates and had lower mortality estimates than largemouth bass captured on octopus hooks (i.e., a variation on the J-style hook). However, circle hooks captured 50% fewer fish. In another study, Cooke et al. (2003b) determined that circle hooks performed similarly to baitholder, Aberdeen, and wide-gap hooks (i.e., all variations on J-style hooks) in both bluegills *Lepomis macrochirus* and pumpkinseeds *L. gibbosus* over a range of water temperatures, but some evidence of size-specific injury was noted related to fish total length (see below). The authors (i.e., Cooke et al. 2003b) hypothesized that circle hooks may perform optimally if hook size was matched to a specific size of fish.

There currently are no studies that have investigated the possible relationship between circle hook size, fish size, and hook performance (in terms of hooking efficiency and minimizing injury and mortality). To date, evidence suggests that using intermediate- and similar-sized hooks of different design results in the capture of fish that are of similar size (Lukacovic and Uphoff 2002; Cooke et al. 2003a, 2003b, 2003c). Cooke et al. (2003b) noted that smaller bluegills and pumpkinseeds (<145 mm) captured on circle hooks were hooked more deeply than larger fish (>145 mm). The same trend was not observed in the other three hook types they examined (Cooke et al. 2003b). Furthermore, circle hooks frequently hooked small- and intermediate-sized fish in the eye. Based upon these results and anecdotal observations, these authors surmised that the size of the circle hook may play an important role in their proper function. In circle hooks, the entire hook needs to end up inside the mouth prior to ''setting the hook'' if the hook is to function properly. When the entire hook is in the mouth, the pressure from the ''hook set'' permits the hook to slide anteriorly until it reaches the jaw region where the hook rotates itself into position, usually in the corner of the jaw. This could pose some challenging problems when one considers that the optimal hook size for the targeted species and size of fish may cause substantial injury in smaller or larger fish that are being captured and released and are considered bycatch. Among other hook types, the relationship between hook size, fish size, and hook performance varies widely among studies, perhaps due to interspecific variation. Muoneke and Childress (1994) concluded that further research in the relationship among different hook types, size of hooks, and sizes of fish was warranted.

The purpose of this study was to evaluate the conservation benefits of using circle hooks for angling freshwater fish. In particular, we were interested in testing the hypothesis that hook size needs to be matched with fish size to achieve maximum conservation benefits and hooking efficiency. We also tested the size selectivity of different hook sizes. In this study, we focused on bluegills and varied circle hook size (1/0, 2, 6, 10, and 14) baited with organic bait. We fished in a lake with an abundant bluegill population comprising fish of varied size (juvenile fish to trophy fish) so that we could examine the size-selective nature of different-sized hooks. Bluegills are an important recreational fish, with anglers often targeting trophy-sized individuals. To effectively manage bluegill populations to yield high-quality fisheries, it is important to ensure that catch-and-release mortality is not eliminating desirable size-classes. To that end, the results of this study will be useful for providing management agencies, conservation organizations, and ultimately anglers with direction for determining ranges of hook size for maximizing capture efficiency while minimizing injury and mortality rates for different-sized bluegills.

Methods

Field site.—All angling experiments were conducted in Lake Opinicon, Ontario. Lake Opinicon is a mesotrophic natural lake in eastern Ontario with abundant populations of rock bass *Ambloplites rupestris*, largemouth bass, smallmouth bass *M. dolomieu*, and, in particular, bluegills and pumpkinseeds. Angling was conducted from a 4-m barge or from docks that extended out in the lake to a depth of at least 1 m. Experiments were conducted between May 23 and June 8, 2002, and water temperatures at that time ranged from 15°C to 22°C. Cooke et al. (2003b) reported that mortality was uniformly low for bluegills at 18, 22, and 26°C in Lake Opinicon, so water temperature was not considered to be an important factor in influencing hook performance in this study. We captured 100 bluegills on each hook size. We fished within the large littoral zone of Lake Opinicon, usually drifting so it was extremely unlikely that we recaptured the same individuals repeatedly or that fish became wary of the baited hooks.

Experimental protocol.—We used commercially available barbed circle hooks for this study that

TABLE 1.—Characteristics of circle hooks (Lazer Sharp Featherlite Finesse nickel Teflon freshwater circle sea hooks, Model L702G, Eagle Claw, Inc.) used in study.

Manufacturer's hook size	Stock size (mm)	Outside bend measurement (mm)	Shank-to-point measurement (mm)	Total hook length (mm)
1/0	1.26	16.82	8.64	26.48
2	0.92	13.08	6.62	21.40
6	0.76	11.30	5.16	18.04
10	0.62	8.42	4.64	12.74
14	0.48	6.40	4.10	10.20

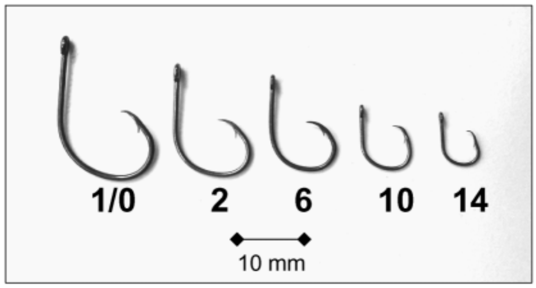

FIGURE 1.—Circle hooks used in hooking experiments.

are appropriate to target bluegills and are widely available in retail stores (Lazer Sharp, Featherlite Finesse nickel Teflon freshwater circle sea hooks, Model L702G, Eagle Claw, Inc., sizes 1/0, 2, 6, 10, and 14; Table 1; Figure 1). All anglers used the same organic bait (Crappie Nibbles, silver glitter; Berkley, Inc.) that measured 5 × 5 mm and weighed ~0.2 g each. Only one Crappie Nibble was used on an individual hook at any one time. All anglers fished with spring floats (⅜-in pencil, 2-in stem [1 in = 2.54 cm]) placed about 0.75 m above the hook. A single 3/0 lead split shot was placed 0.15 m above the hook. Anglers used spinning reels with medium action rods and a 6-lb test line. Anglers rotated fishing rods at 10-min intervals to ensure that all participating anglers fished using the different hook types. All anglers in this study had similar levels of angling experience that could be classified as intermediate.

Anglers were instructed to cast the bait and let the weight and Crappie Nibble settle until the float was upright. The anglers were told to wait for the bobber to go under the surface of the water prior to collecting slack line and gently pulling up on the rod as instructed by the hook manufacturer. Instructions on circle hook packaging indicated that strong hook sets were not required (i.e., ''on the take, do not set hook; just reel fish in;'' Eagle Claw, Inc.). Following the hooking of a fish, we standardized the duration of time that the fish was on the line to 15 s. This interval was sufficient to ensure that all fish could be easily landed without creating undue exhaustion for the fish.

Upon capture, the anatomical location of the hook (jaw, roof, eye, or gullet) was determined and recorded. The location of hook penetration was measured from the anterior aspect of the (lower) lip to the deepest (i.e., most posterior) point of hook penetration (Dunmall et al. 2001). Ease of hook removal was categorized using slight modifications to the criteria proposed by Cooke et al. (2001). Hooks that were removed by hand with little effort were categorized as ''easy.'' If hemostats were required to remove the hook, it was categorized as ''difficult,'' and if removal of the hook would have caused substantial injury to the fish, the line was cut and the hook was categorized as ''not possible.'' After assessing ease of hook removal, the angler examined the fish for the presence of blood and recorded responses as ''none,'' ''some,'' or ''extreme'' following the methods of Cooke et al. (2003b). The fish were also measured for total length (mm). We used total length to size correct the depth of hook penetration (into relative hooking depth units), permitting a comparison of hook penetration depth among fish of different sizes (Dunmall et al. 2001). Hook depth was expressed as a proportional location of the hook from the snout relative to the total length of the fish. Gape size was measured (0.5 mm) from the inner medial aspect of the sides of the snout when the mouth was open using a manual caliper set. We also monitored the number of missed fish (fish that hit or nibbled but were absent upon taking up the slack in the line) and the number of fish that escaped during the 15-s fight, and recorded the frequency of occurrence of misses or losses upon landing an individual bluegill. When a fish was ''missed,'' the angler recast the bait and continued to monitor for additional misses. Air exposure durations were less than 60 s, including removal of hook and enumeration. Using criteria similar to Milne and Ball (1956) and Cooke et al. (2003b, 2003c), we assessed mortality using mortality projections. Our previous work with bluegills suggested that most mortality was immediate and resulted from the violation of vital tissue (e.g., gill arches, pericardial cavity, ventral aortal) and severe bleeding (e.g., Pelzman 1978). When hooked in nonvital tissues and when bleeding was minimal, most bluegills will survive the angling experience at the water temperatures used in this study (Cooke et al. 2003b). Using these criteria, fish were classified as either ''likely survivors'' or ''likely mortalities.'' In total, we landed 100 fish on each of the five hook types.

Analyses.—Continuous data were not transformed because they were determined to be normally distributed with homogeneous variances. Homogeneity of variance assumptions were assessed using Levene's test and normality was verified using normal probability plots and the Shapiro–Wilk test statistic. Differences in total length, depth of hook penetration, and relative hooking success index values among different hook sizes were assessed using a one-way analysis of variance (ANOVA). When differences were observed, we used Tukey's honestly significant difference (HSD) tests for mean separation. Categorical data were analyzed with chi-squared contingency table analysis. To examine the size selectivity of the different hook types, we used data obtained from the Ontario Ministry of Natural Resources Trap Netting Program (OMNR, unpublished file data) on Lake Opinicon that was conducted on their behalf by our research group. We used the total length distribution (including relative abundance) for all bluegills encountered in late summer trap nets ($N = 339$). We compared individually the total length distribution of fish captured on the five different hook types to the expected distribution based upon the trap net data using two-way Kolmogorov–Smirnov (KS) tests. Analyses were conducted using JMP 4.0 (SAS Institute, Inc.) except for the two-way Kolmogorov–Smirnov test that was executed using SYSTAT 10.0 (SAS Institute, Inc.). All values reported are means ± SE. All tests were assessed for significance at the $\alpha = 0.05$.

Results

The number of fish missed differed by circle hook size (ANOVA: $F = 16.12$; df = 4, 95; $P < 0.001$; Figure 2A). Most fish were missed when anglers were using the largest hook size (1/0), with approximately two misses per fish landed, nearly twice the number of misses than that observed using other hook sizes. The number of fish lost by anglers also differed by hook size (ANOVA: $F = 2.72$; df = 4, 95; $P = 0.029$; Figure 2B). However, the posthoc analyses did not identify any significant differences, but sizes 1/0 and 2 were only marginally nonsignificant ($P = 0.051$). In general, the largest- and smallest-sized hooks (1/0 and 14, respectively) lost more fish than intermediate-sized hooks; however, overall loss rates were generally quite low (i.e., less than one fish lost for every eight fish successfully landed).

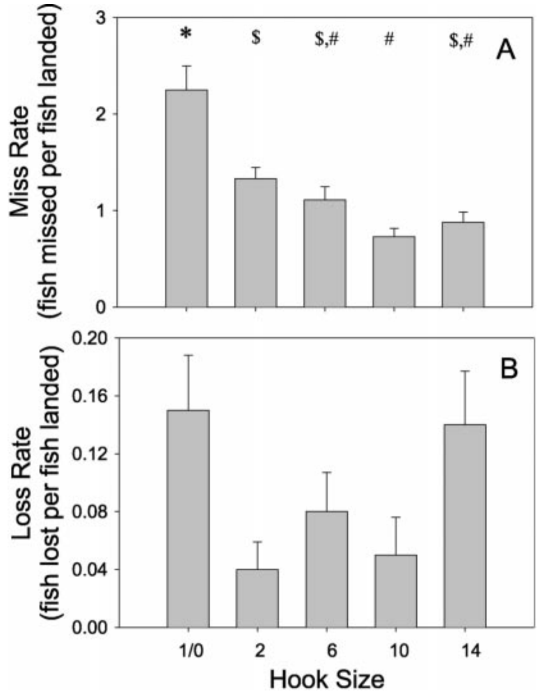

FIGURE 2.—Panel **(A)** shows the mean (+SE) miss rate of bluegills captured on circle hooks of different sizes; dissimilar symbols represent statistically significant differences ($P < 0.05$; Tukey's highly significant difference test). Panel **(B)** shows the mean (+SE) loss rate of bluegills captured on circle hooks of different sizes; no significant differences were noted using Tukey's test ($P > 0.05$).

The size of fish captured differed significantly across hook sizes (ANOVA: $F = 20.44$; df = 4, 95; $P < 0.001$; Figure 3A). There was a general trend of larger fish being captured on larger hook sizes and smaller fish being captured on smaller hook types. All five hook sizes experienced size selectivity with respect to the relative abundance of different-sized fish in the lake determined from trap-netting (1/0: KS = 0.18, $P = 0.016$; 2: KS = 0.38, $P < 0.001$; 6: KS = 0.29, $P < 0.001$; 10: KS = 0.47, $P < 0.001$; 14: KS = 0.61, $P < 0.001$). In all cases, the distribution of the fish captured by the different-sized hooks was shifted towards smaller individuals. Interestingly, only the fish captured on the largest hook size (1/0) had a size distribution that was not highly significantly different (i.e., not $P < 0.001$) from the distribution of fish sized in the lake. In addition, the mean KS

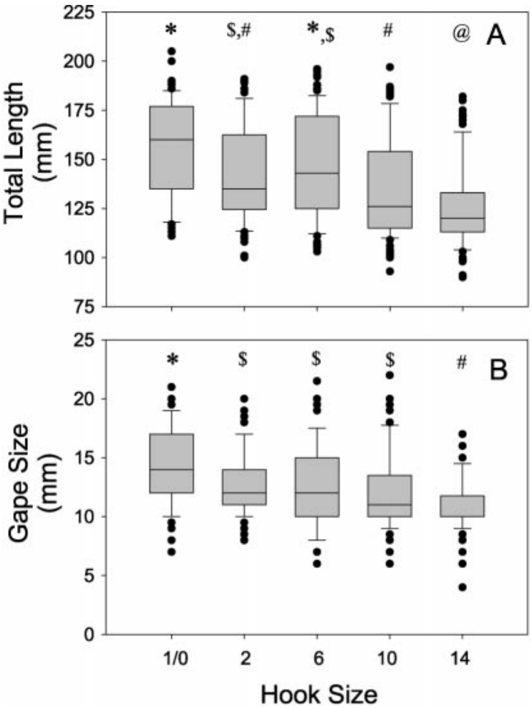

FIGURE 3.—Panel **(A)** shows the selectivity of five sizes of circle hooks for bluegills. The box plots represent the total lengths (mm) of 100 fish for each hook size; the horizontal lines represent the means, the circles outliers, and the whiskers the 90th percentiles. Panel **(B)** shows the variation in gape size among fish captured on circle hooks of different sizes; the box plots represent gape size (mm) of 100 fish for each hook size. In both panels, dissimilar symbols represent statistically significant differences ($P < 0.05$; Tukey's highly significant difference test).

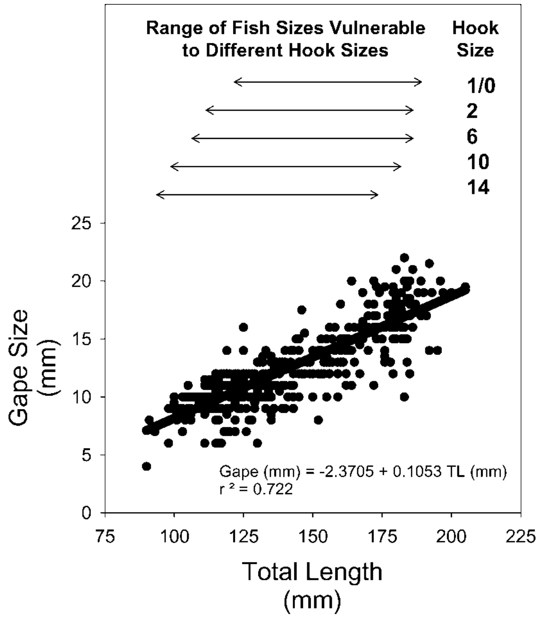

FIGURE 4.—Relationships between the total length (mm) and gape size (mm) of 500 bluegills captured on circle hooks of different sizes. The ranges of optimal hook sizes for different-sized fish are portrayed in the upper panel. Optimal values were determined qualitatively using information on the outside bend size of the hooks (Table 1) and the gape size of the fish.

difference tended to increase with decreasing hook size, illustrating growing departure from the distribution of fish sizes in the lake.

The mean gape size of fish also varied significantly with hook size (ANOVA: $F = 18.64$; df $=$ 4, 95; $P < 0.001$; Figure 3B). The largest hook size (1/0) captured fish with the greatest mean gape sizes, and the smallest hook size (14) captured fish with the smallest mean gape sizes. Fish captured on other hook sizes (2, 6, and 10) captured fish with intermediate gape sizes. Because of the strong relationship between gape size and total length (Figure 4) and the variation in hook size, we were able to plot the outer bend of the hook (Table 1) in conjunction with the minimum gape size and the associated fish sizes to determine the vulnerability of different-sized fish to capture by different hook sizes (Figure 4).

Length-corrected mean hooking depth did not vary significantly by hook size (ANOVA: $F = 0.83$; df $=$ 4, 95; $P = 0.509$), most fish being hooked about 0.045 relative hooking depth units from the anterior aspect of the snout (location of the hook from the snout/total length). Only fish captured on size 6, 10, and 14 hooks were hooked greater than 0.10 relative hooking depth units from the anterior aspect of the snout.

Although anatomical hooking locations differed across hook sizes ($\chi^2 = 37.80$; $P < 0.001$; Figure 5), the results should be viewed with some circumspection due to low expected values in some contingency table cells. There was a general trend of more fish being hooked in the jaw and fewer fish hooked in the roof of the mouth with decreasing hook size. The two largest hook sizes experienced the greatest level of eye hooking, but no gullet hooking was observed. Conversely, smaller hook sizes exhibited reduced eye hooking but increased gullet hooking (Figure 5).

Despite variation in anatomical hooking locations, no differences in ease of hook removal were noted ($\chi^2 = 12.03$; $P = 0.150$). In general, most hooks were easy to remove, with only 6 fish out

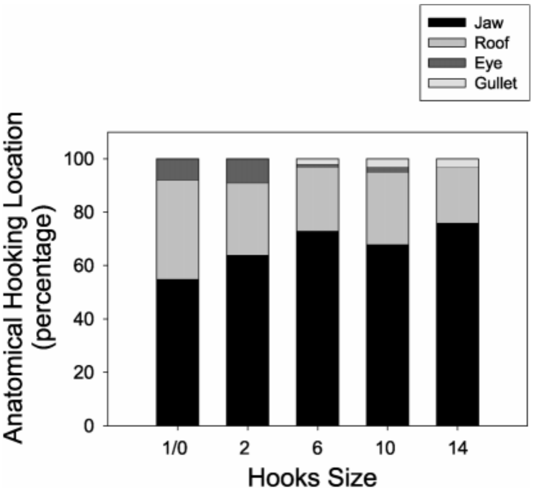

FIGURE 5.—Anatomical hooking locations for bluegills captured with circle hooks of different sizes. Hooking locations were classified as jaw (including upper, lower, and side), roof of the mouth, eye, or gullet.

of 500 hooked so deeply that the hook could not be removed. Bleeding was generally low among all hook sizes and did not vary significantly across hook sizes ($\chi^2 = 8.13$; $P = 0.164$). Bleeding rates ranged from 1% to 8% and were never classified as ''extreme.'' Mortality risk ratings were also generally low and did not differ across hook sizes ($\chi^2 = 3.39$; $P = 0.496$). For all hook sizes, mortality ranged from 0% to 2% of individuals.

Discussion

In our study, we observed differences in the number of fish missed and lost among different hook sizes. For bluegills, the largest hook size (1/0) resulted in the highest miss and loss rate. The higher miss rate is likely attributable to smaller fish that were unable to fit the entire hook in their mouth and therefore rarely became hooked when being reeled in. Other researchers have reported similar trends of hooking efficiency decreasing with increasing absolute hook size in a fishery for snapper *Pagrus auratus* (Otway and Craig 1993). The smallest hook size also had high loss rates, likely due to the difficulty in securely hooking larger fish. Although the fish captured on the largest and smallest hooks were lost most frequently, these loss rates were quite low (i.e., ~0.10 fish lost for every fish landed) and were much less disparate than observed elsewhere.

Consistent with the trend in hooking efficiency, we also observed substantial differences in fish size associated with circle hooks of different sizes. Small hooks tended to capture smaller fish, and larger hooks tended to hook larger fish. Similar observations have also been reported by Otway and Craig (1993) who suggest that snapper caught on size 8 circle hooks were larger than those captured on size 10 or 12 hooks. Interestingly, however, in another study of bluegill hooking, fish captured on four sizes of regular shank J-style hooks (4, 6, 8, and 10) did not differ in length (Burdick and Wydoski 1989). Based upon our measurements of hook size (Table 1) and gape size we suggest that smaller fish in our study were physically unable to fit the entire hook in their mouth (Figure 4). However, if fish took part of the hook in their mouth and, in particular, the point, it was possible to hook small fish with large hooks, usually in the roof of the mouth. Large circle hooks, therefore, may simply not be able to function properly in small fish. Otway and Craig (1993) also reported that increasing hook size did not eliminate the capture of smaller fish. The trend for smaller hooks to not catch larger individuals may be due to the small gape between the point and shank of the hook, which must fit over the jaw region to function properly.

Not only did the use of different hook sizes capture fish of different sizes, these different-sized hooks also exhibited size selectively. All of the hook sizes that we used in our study resulted in the capture of individuals that differed significantly in size (smaller) relative to the distribution of fish sizes in the lake (larger). The distribution of fish sizes captured on the largest hook size (1/0) did exhibit increased conformity with the distribution of fish sizes in the lake (although still significantly different; $P = 0.015$ for largest hook size relative to all Ps < 0.001 for other hook sizes) relative to the other hook sizes. Thus, perhaps a larger hook size may have captured more large individuals and consequently reduced size selectivity. However, it is unlikely that an even larger hook size would be able to capture small fish as well. It is also possible that larger fish were less vulnerable to angling or that trap nets are selective towards the capture of larger individuals.

Cooke et al. (2003b) used size 6 hooks to capture bluegills and suggested that a smaller hook size may have resulted in hook performance that was consistent with the low injury rates and hooking mortality of marine circle hook studies. Our results suggest that there are indeed optimal-sized hooks for hook performance. Because smaller fish may be physically unable to swallow or ingest large hooks (Muoneke and Childress 1994), opportunities for deep hooking when using large hooks may be reduced, as was observed in our study. Fish captured on larger hooks, although larger than those captured on smaller hooks, were never hooked in the gullet. Despite trends in decreased jaw hooking with increased hook size, jaw hooking rates in this study were generally high, exceeding more than 50% for all sizes and approaching 75% for smaller hook sizes. These jaw hooking rates, however, are still somewhat lower than the jaw hooking rates observed in many marine studies (e.g., striped bass *Morone saxatilis*: 97% [Caruso 2000]; bluefin tuna *Thunnus thynnus*: 96% [Skomal et al. 2002]; and summer flounder *Paralichthys dentatus*: >80% [Zimmerman and Bochenek 2002]) but similar to those found in other freshwater studies (e.g., pumpkinseeds: 35% [Cooke et al. 2003b]; bluegills: ~60% [Cooke et al. 2003b]; largemouth bass: 89% [Cooke et al. 2003c]; and rock bass: 76% [Cooke et al. 2003a]).

Although we did observe some bleeding in our study, it was considered minor. Bleeding was generally observed in fish that were hooked in the eye, gullet, or roof of the mouth. Consistent with our low rates of bleeding and anatomical hooking locations, mortality rates based upon our assessment of mortality risk were quite low in our study. These low mortality rates are consistent with the results of other recent research conducted on bluegills using Crappie Nibbles (3%, Cooke et al. 2003b). Studies of bluegill hooking mortality conducted in other locations that did not use circle hooks report mortality rates ranging from 0% to 88% (Burdick and Wydoski 1989; Siewert and Cave 1990; Muoneke 1992). Burdick and Wydoski (1989) indicated that mortality in bluegills varied with hook size but generally increased with decreasing hook size (i.e., size 4, 7%; size 6, 10%; size 8, 18%; and size 10, 10%). In our study, such patterns were not apparent.

In this study we did not compare circle hooks with other hook types since this has previously been done (e.g., Cooke et al. 2003b). However, injury rates and mortality projections were generally low. Circle hook performance definitely varies widely among species based upon factors such as mouth morphology, mode of feeding, and dentition. Although circle hooks did not eliminate deep hooking, the frequencies of deep hooking were extremely low compared with other studies in which organic baits and similar-sized hooks were employed. These results are also rather consistent with existing studies of circle hooks in marine fisheries where gullet hooking is infrequent and mortality is low when using circle hooks (e.g., Caruso 2000; Skomal et al. 2002; Cooke and Suski 2004).

The choice of proper hook size seems to be especially important for the proper function of circle hooks if they are to provide reasonable conservation benefits. The research we report here presents some practical difficulties because anglers typically will use larger hooks to target larger fish, some of which may be harvested, but the larger hooks may cause more damage to smaller fish that will inevitably be released (e.g., eye hooking). Conversely, if anglers use smaller hooks to target smaller fish, larger fish would likely ingest the smaller hooks more deeply (e.g., gullet hooking), or they would function less efficiently. Our results suggest that it is not possible to eliminate the capture of small fish by using larger hooks. Large hooks do result in some size selectivity towards larger fish; however, they do hook smaller fish. Although difficult to rigorously define, intermediate-sized hooks would provide reasonable tradeoffs between injury and capture efficiency. More research is needed to quantify the relationships between circle hook size and injury and mortality rates. The challenge lies in choosing hooks that are appropriate for minimizing bycatch injury and mortality while maximizing the capture efficiency of target fish when the size of the potential fish to be angled is unknown. Previous research by our group using size 6 hooks of four different kinds suggested that circle hooks were not very effective conservation tools for sunfish (Cooke et al. 2003b); however, our current study suggests that hook size does play a role in how circle hooks function. Thus, using circle hooks of an appropriate size does have the potential to contribute to sunfish conservation. It would be instructive to know how circle hook size alters injury or mortality rates for species such as billfish or tuna where circle hooks have made positive conservation impacts.

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